Public Perceptions of PFAS

Aysha Riaz

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Charlotte Lester

Introduction

- Research commissioned by The Royal Society of **Chemistry** and delivered by **YouGov**.
- Over **4000** respondents representative of the UK population in individual demographics and geography.
- Two focus groups.
- Highlighting the public **priorities** in relation to PFAS.

Scan me for full report and data!

Why is this important?

- We know PFAS do no easily break down and build up over time in humans, animals and the environment.
- They are CECs – often not controlled or monitored.
- Our knowledge of toxicity levels of PFAS is varied.

Scan me for full report and data!

Evidence and understanding of public views and priorities on PFAS

Contextualising findings within wider policy evidence base

Help regulators effectively manage manufacture, use and disposal

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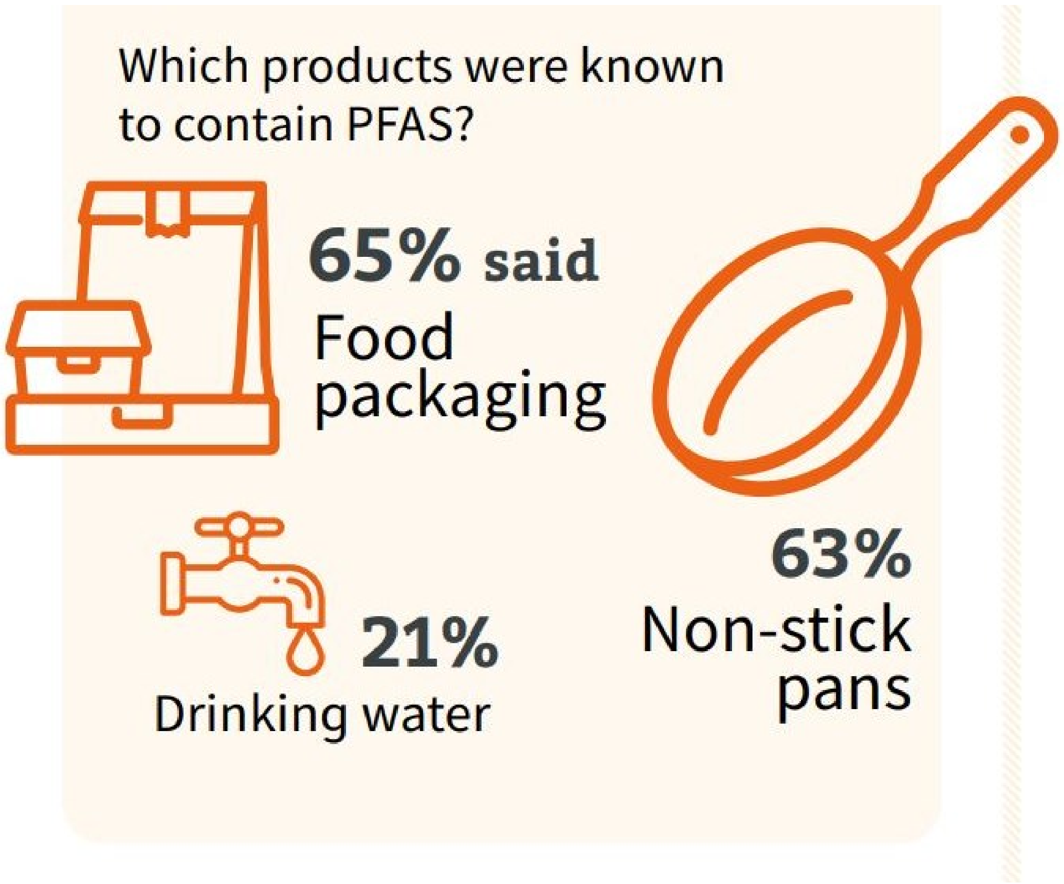
Awareness of PFAS

67% of the general public were not aware of PFAS

The RSC considers transparency and citizens’ right to know as two important principles for the management of chemicals in the environment.



Awareness of PFAS

72% said they were unlikely to have avoided purchasing a product containing PFAS in the past because they did not know enough about PFAS.

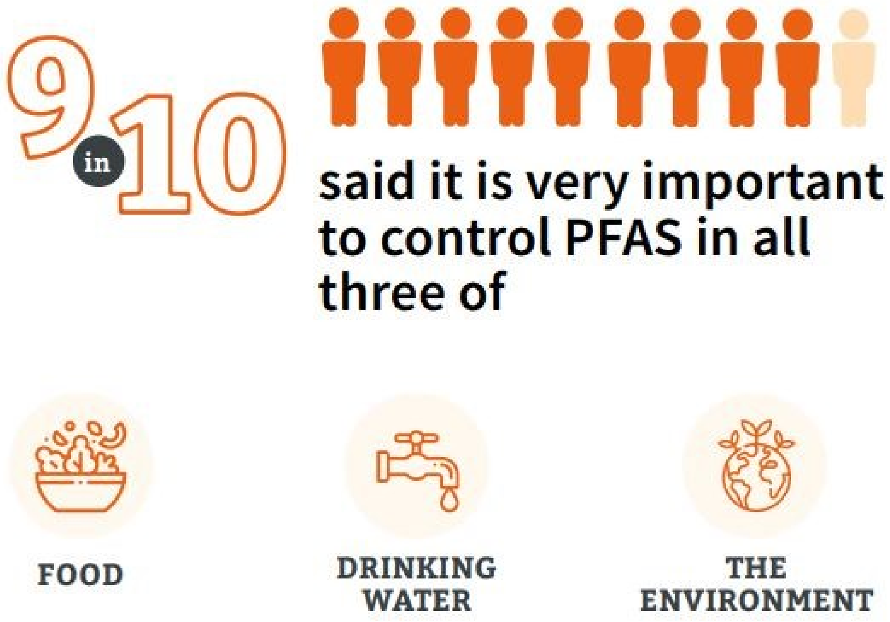
Mixed opinions if **all**, **some** or **no** PFAS poses risk to the environment and human health.

Participants expressed desire for better public and consumer information.

“This has been a great experience... I think these type[s] of sessions are great for captur[ing] public opinion but also help to educate and stimulate ideas to help society make positive changes.”

Focus group participant

Taking action on PFAS



Who should take responsibility for reducing PFAS levels?

- Chemicals manufacturers **74%**
- Product manufacturers **73%**
- UK Government **58%**

Trust to take action is low

- UK government **29%**
- Individual consumers **27%**
- Manufacturers of chemicals or products **14%**

Taking action on PFAS

Focus Group Priorities:

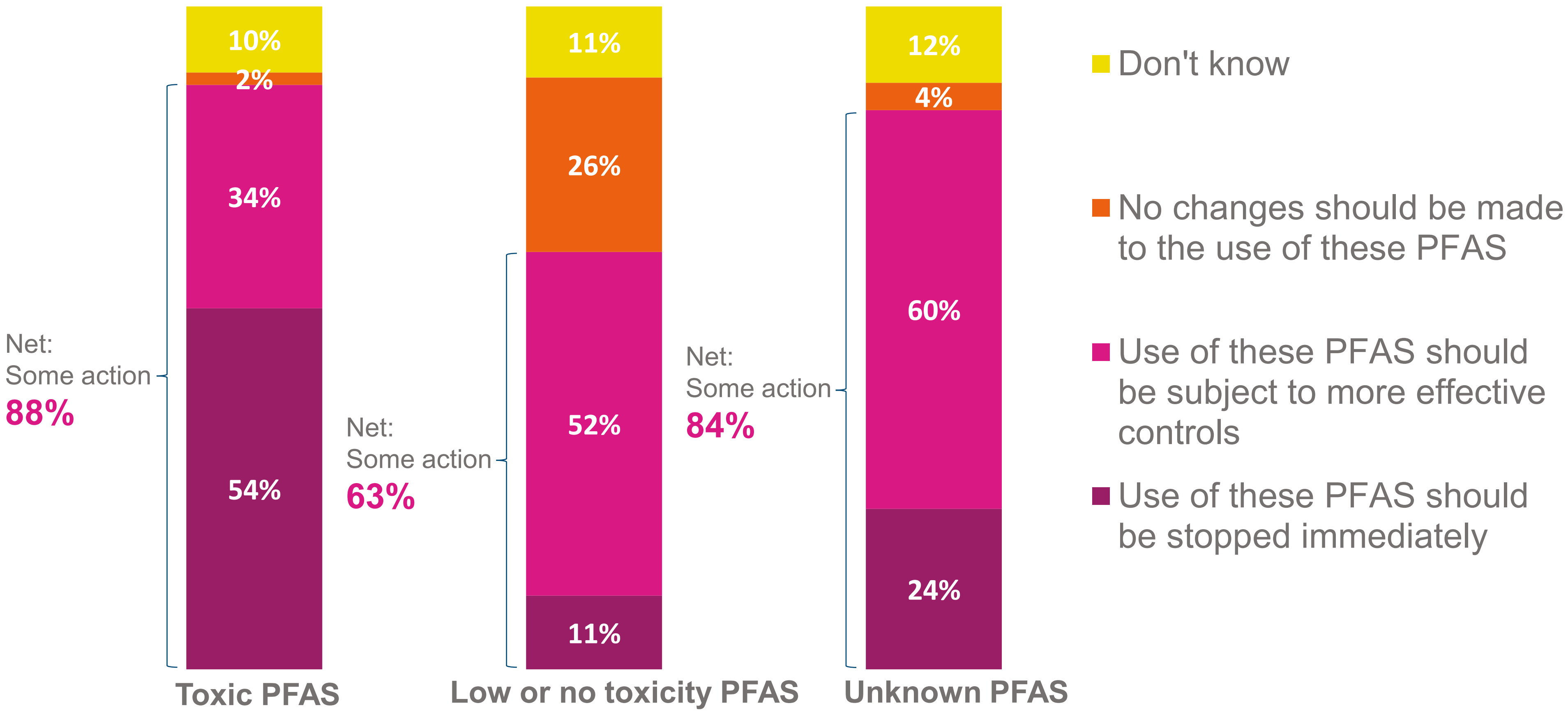
Government's responsibility to enforce PFAS laws and regulations.

Trust in charity organisations with clarity on funding.

Information be verified by credible organisations/experts.

Management of PFAS

Preferred management of PFAS



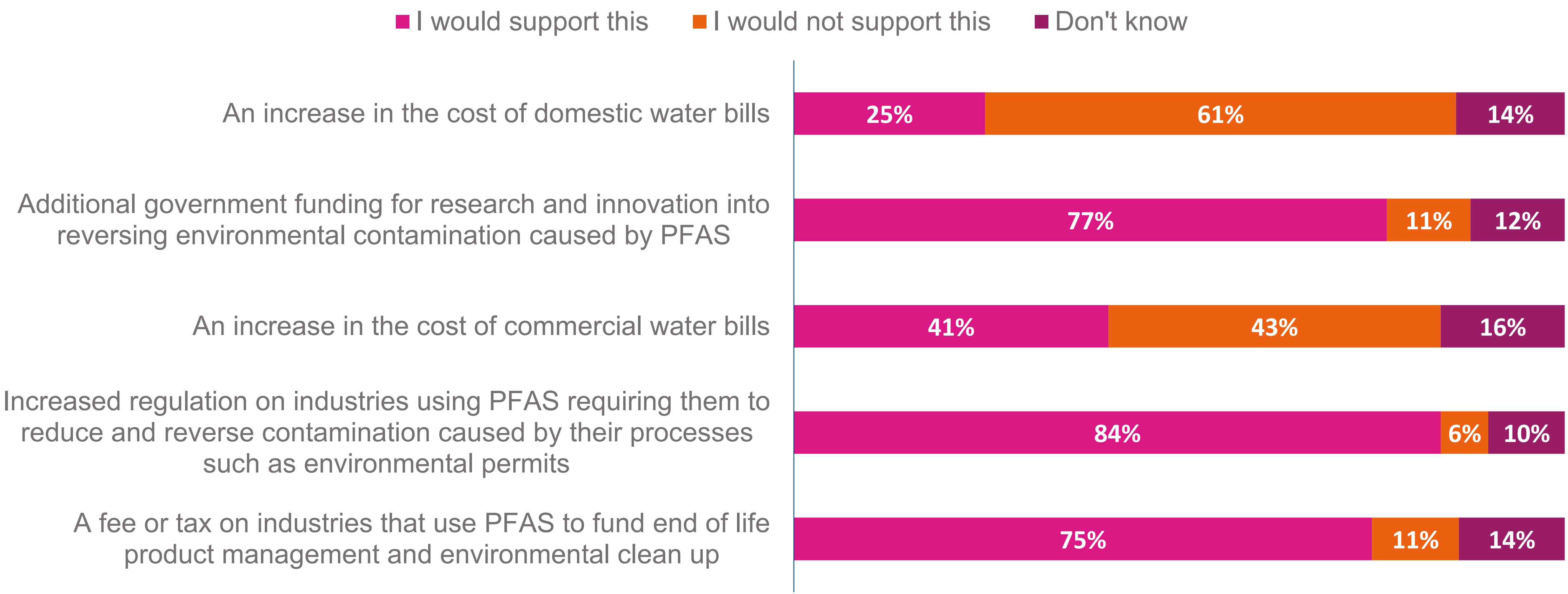
Management of PFAS

The RSC proposes a risk-based approach for the management of PFAS across their lifecycle. → Around half of respondents who wanted more effective controls preferred a risk-based approach

Take into account the precautionary principle. → Focus group participants agreed for PFAS of unknown toxicity

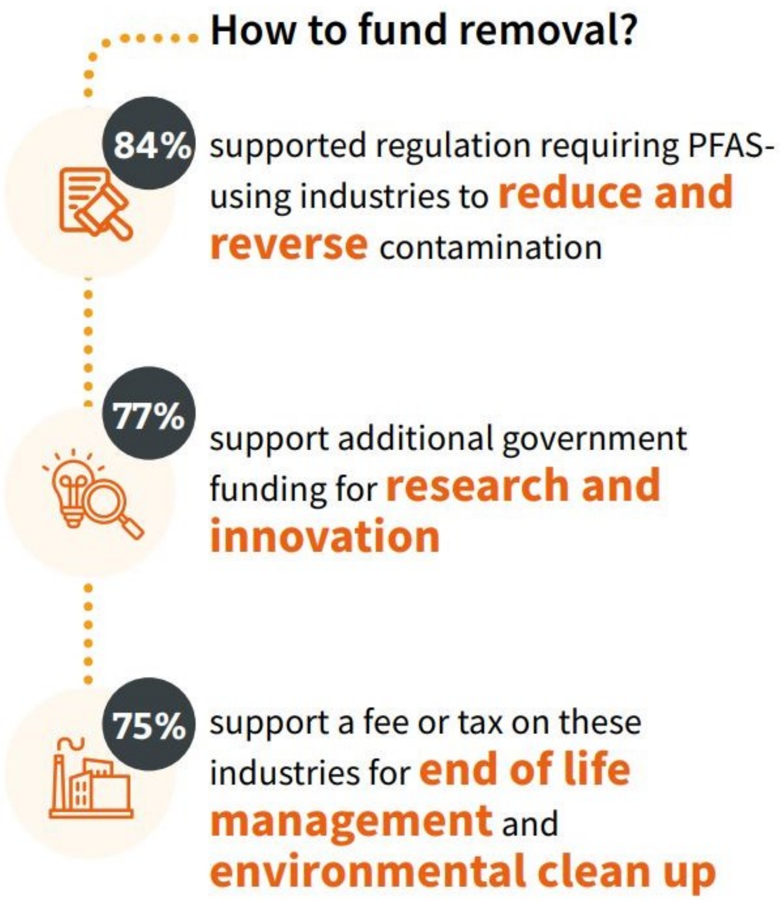
Understand essential uses and alternatives to inform decisions → Only 3 in 10 wanted an essential uses approach

Support for measures to fund the removal of PFAS from the environment



Base: all survey respondents (n=4,194)

Management of PFAS



UK Government to have comprehensive monitoring programme for CECs

Industrial users of PFAS must test wastewater discharges and apply appropriate treatment/removal

Central and public database to record PFAS

UK Government implement ‘polluter pays’ principle funded by industries that produce problematic PFAS

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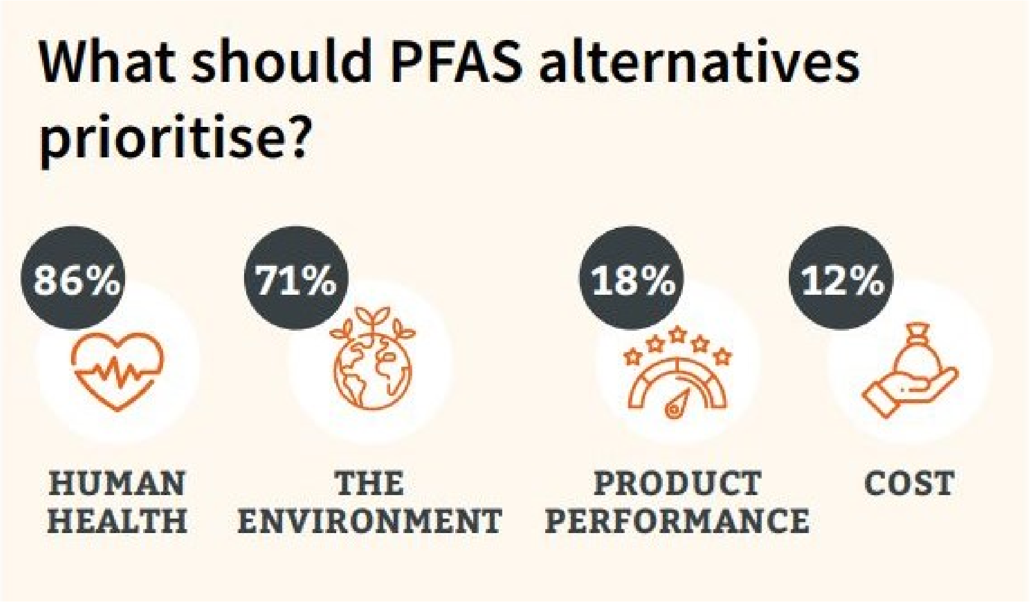
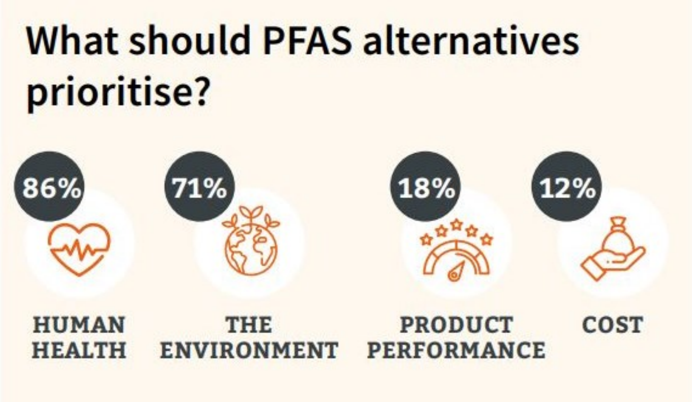
Alternatives to PFAS

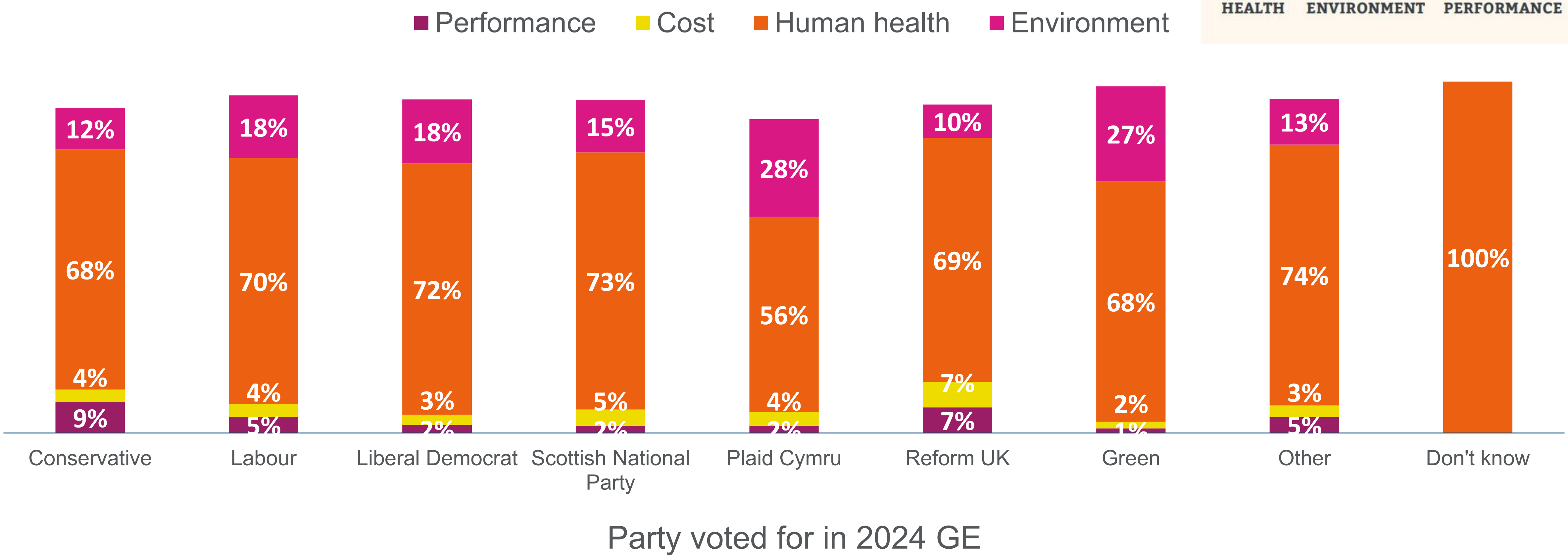
The **RSC-YouGov** study asked questions about the use of PFAS versus **alternatives** to understand the trade-offs people are willing to accept.

People want alternatives to PFAS that will **not** negatively impact their **health** or the **environment.**



Number one priority for PFAS replacements by voting behaviour





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Alternatives to PFAS

Willingness to accept changes to products if toxic PFAS weren't used:

- Lower performance **61%**
- Increased cost **60%**
- Reduced availability **70%**

Some key thoughts:

Cost not increased significantly for products deemed necessities – avoid increasing socio-economic inequality .

Participants recognised trade-offs for highly specialised sectors where PFAS substitutes are not available – type or variety of products accessible may be affected.

Majority felt it's the manufacturers responsivity to research and implement easily accessible alternatives – no offloading costs to consumers.

The types of changes that are acceptable depend on the type of product.

Alternatives to PFAS

Focus Group Participants

Focus group participants wanted **more information** about products they use. **Labelling** and product information was viewed as an important way to make more informed choices.

They also expressed frustration with perceived **lack of investment** into **safer alternatives** and current lack of market alternatives.

Conclusion

This research complements a large body of scientific policy evidence and demonstrates clearly that people care about PFAS and want to see **change** as soon as possible and that the Government should too!

The **RSC's** Cleaning up UK drinking water campaign, launched in 2023, has already contributed to **more stringent guidance** on PFAS levels in drinking water.

We will continue to engage with policy makers, scientific evidence, stakeholders and the **public** to work towards **sustainable** and meaningful change for PFAS use and management.

Find out more!

Per- and polyfluoroalkyl substances (PFAS) in UK drinking water (2023)

Risk based regulation for per- and polyfluoroalkyl substances (PFAS) (2021)

Tackling Contaminants of Emerging Concern (CECs) in water (2024)

A chemicals strategy for a sustainable chemicals revolution (2020)

Thank you to **Stephanie Metzger** and the rest of the RSC P&E Team, **Charlotte Lester** of the RSC Public Engagement and Outreach Team, and **Neil Clark** of the RSC. Thanks to the team at **YouGov** for conducting the survey work. Thanks also to **Sarah O'Reilly** and **Chris Gooch** for editing and design.

Thank you!

The RSC would be happy to discuss any of the issues raised in this work in more detail. Contact the RSC Policy & Evidence Team at **policy@rsc.org**

Designing for the circular economy

Izzi Monk

Policy Adviser, Environment

6 February 2025

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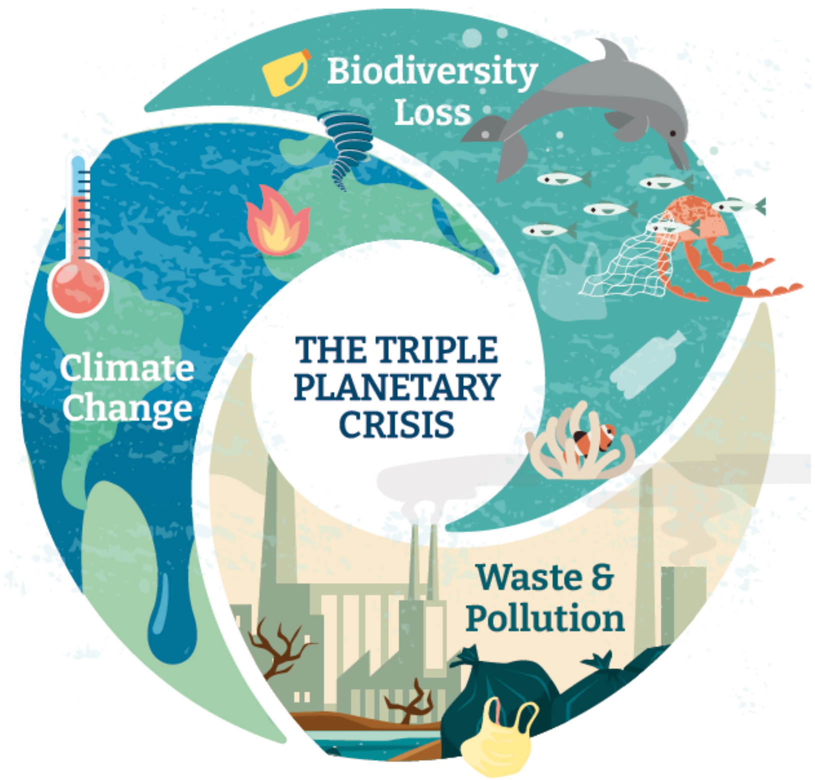
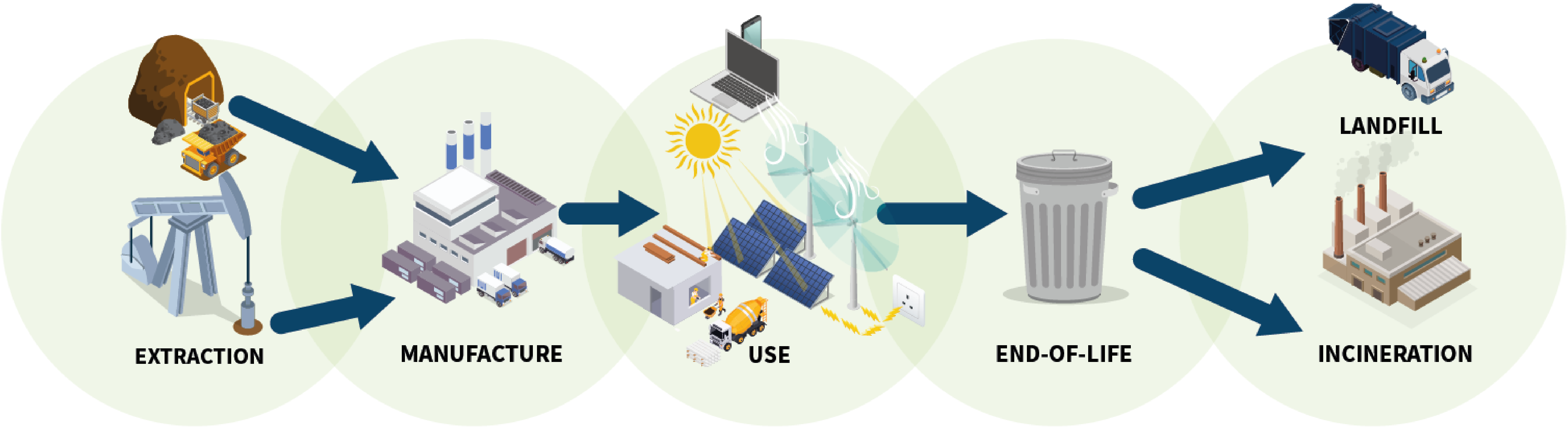
Why do we need a circular economy?

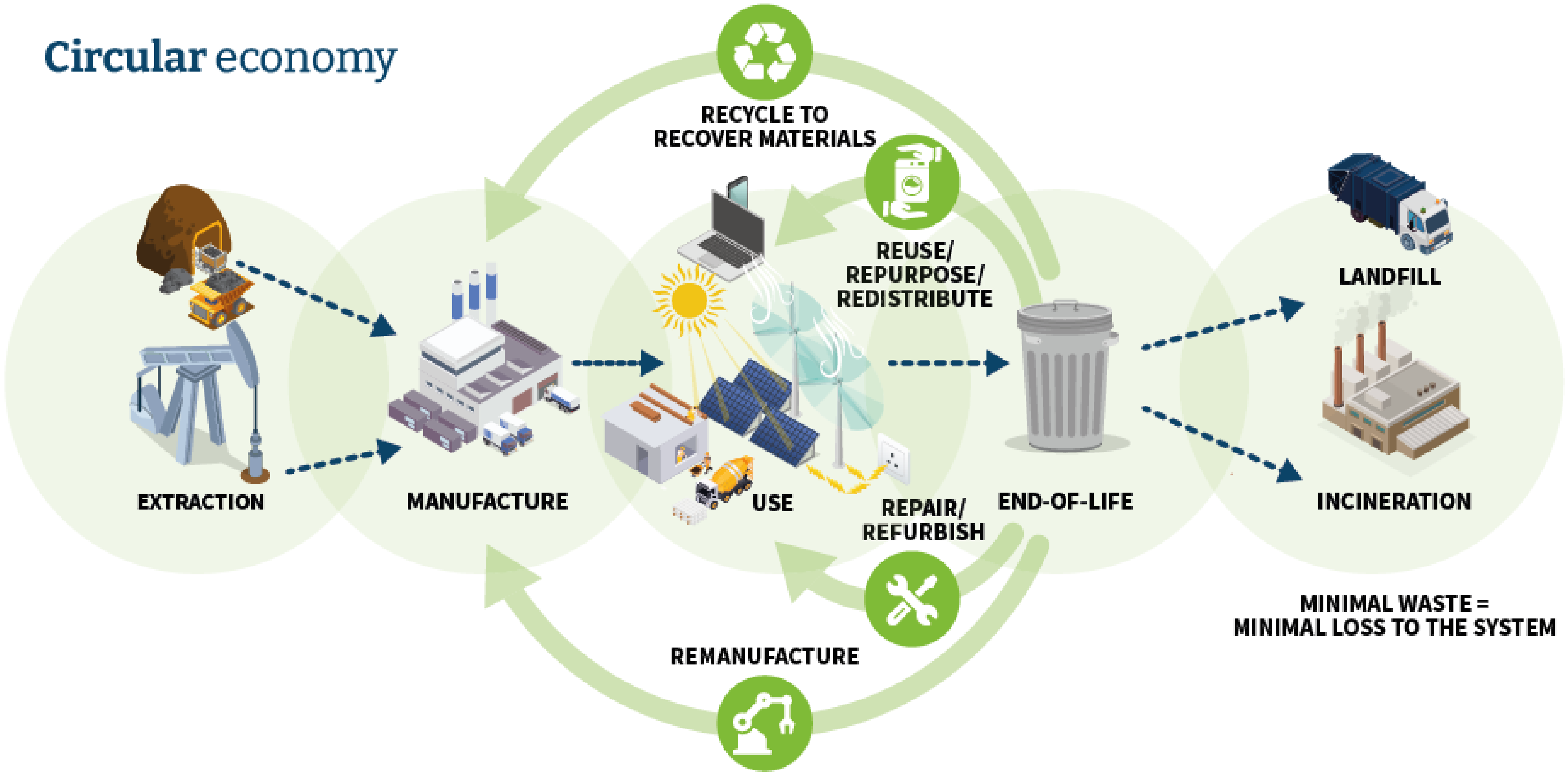


Linear economy

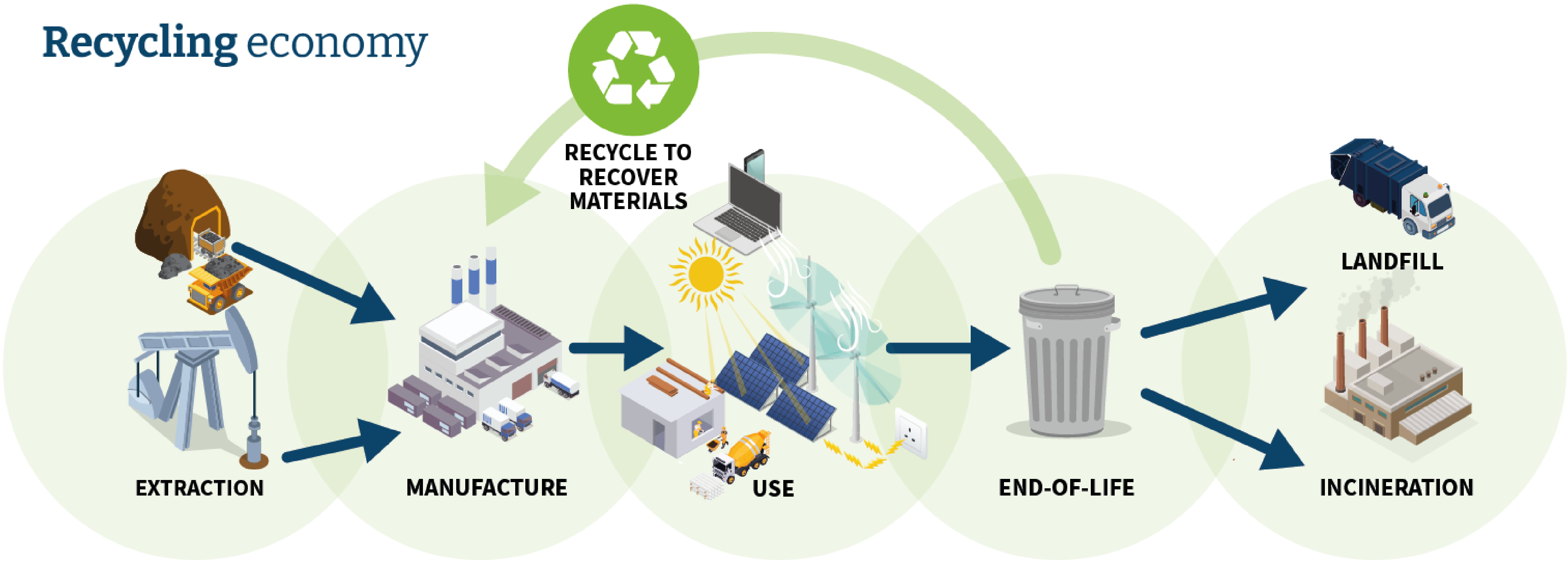


WASTE = LOSS TO THE SYSTEM

Circular economy



Recycling economy



Designing for circularity

- Consider whole lifecycle of PFAS alternative
- Avoid ‘regrettable substitution’ and ‘burden shifting’
- Understand the trade-offs
- Consider impacts beyond GHG emissions

What will support a move to a circular economy?

1. Improve data collection, including the mapping and tracking of critical mineral and other material streams
2. **Support world-class research into sustainable materials, including those limiting emissions along entire material and product lifecycles.**
3. **Invest in and incentivise resource-efficient design, production and processes, alongside assessments of criticality and substitutability of materials.**
4. Invest in infrastructure to support the re-use, repair and re-manufacturing of products according to the waste hierarchy.
5. Invest in recycling infrastructure and technologies to enable the increased recovery of critical minerals and other materials.

Any questions?

rsc.li/ewaste

monki@rsc.org

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Overcoming barriers:

Identifying barriers to substitution and methods to overcome them.

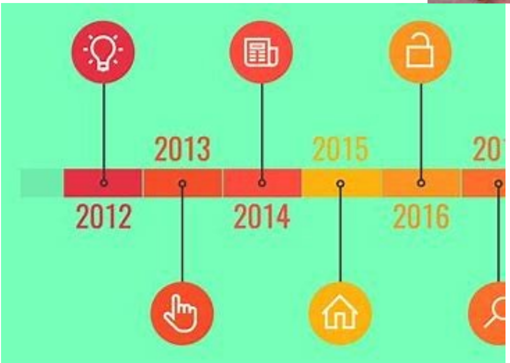
06 Feb 2025

Dr. Karina Reynolds-Young
WSP Environmental Policy & Economics Team

Barriers to developing alternatives and substituting PFAS

ZeroPM
Zero Pollution of Persistent, Mobile Substances

1. Technical standards
2. Regulation
3. Critical uses
4. Information sharing
5. Timescales and costs

Technical standards

Barriers

- Some standards require specific materials be used
- Functionality is well defined and must be met
- Standards are throughout an industry
- Standardization is expensive and time consuming

Opportunities

- Future proof standards by focusing on functionality instead of specific materials
- Collaborate within industry to advance standards
- Collaborate with standards authorities to help understand the use of PFAS and potential for alternatives
- Collaboration between industries for articles that have multiple functions
- Review standards more often

Regulation

Barriers

- Overall regulatory timeframe can be slow (proposal, consultations, and implementation)
- Little to no communication between regulators and industry/academia regarding future insights
- Lack of regulatory triggers
- Scope and definition used in regulations are not consistent globally

Opportunities

- Improve communication between regulators and industry/academia
- Ensuring regulatory triggers from regulators
- Planning substitution efforts based on strictest regulations
- Well defined time limited derogations

Critical uses

Barriers

- There are no currently feasible alternatives for some critical uses
- Lack of 'one size fits all' alternatives resulting in additional difficulties for critical uses

Opportunities

- Understanding and defining what is truly a critical use
- Accepting individual uses will need tailored substitution/alternatives
- Additional support from R&D to work on critical uses as a higher priority

Information sharing

Barriers

- IP and competition laws
- One article can have many uses within various industries
- Lack of supply chain transparency and traceability

Opportunities

- Development and utilisation of substitution centres
- Use of product passports, especially for articles used by various industries
- Utilisation of academia as an information point

Timescales and costs

Barriers

- Time to substitution can be 10+ years depending on the industry
- R&D and restandardisation are costly
- Time to regulatory decisions and implementation

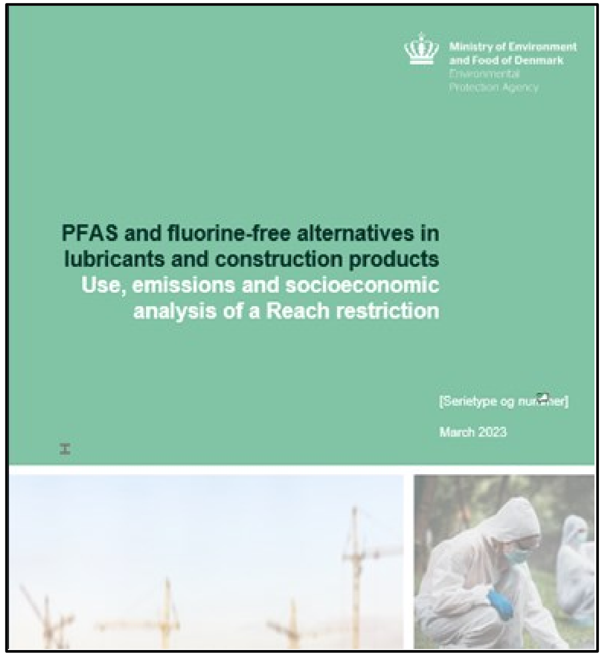
Opportunities

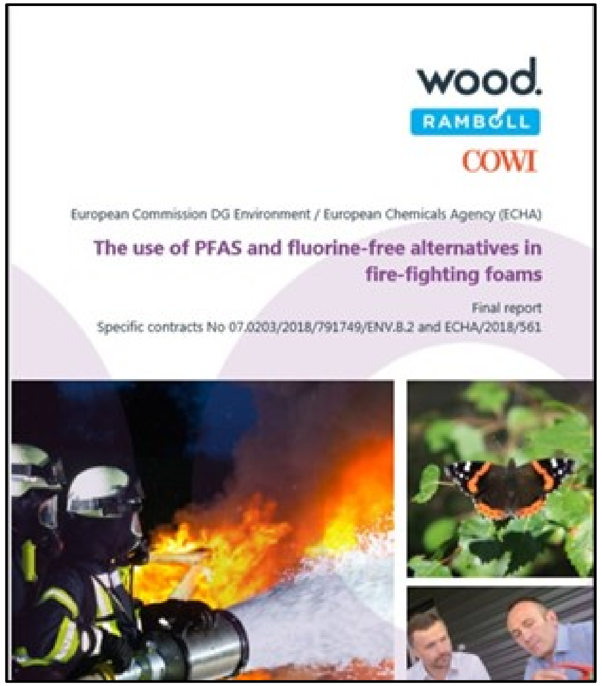
- Continually reviewing regulation and upcoming potential substitution needs
- Communication with regulators regarding timescales
- Additional information sharing/upstream communication

WSP overview

Introduction to WSP

- Environmental policy and economics team
- Large client base (industry, NGOs, and governments)
- Recent work:
  - Assessment of alternative for PFAS in cosmetics, lubricants, construction products, and FFF
  - Support to the PFAS restriction proposal
  - Supply chain mapping of PFAS uses within industries





Thank you

WSP Environmental Policy & Economics Team
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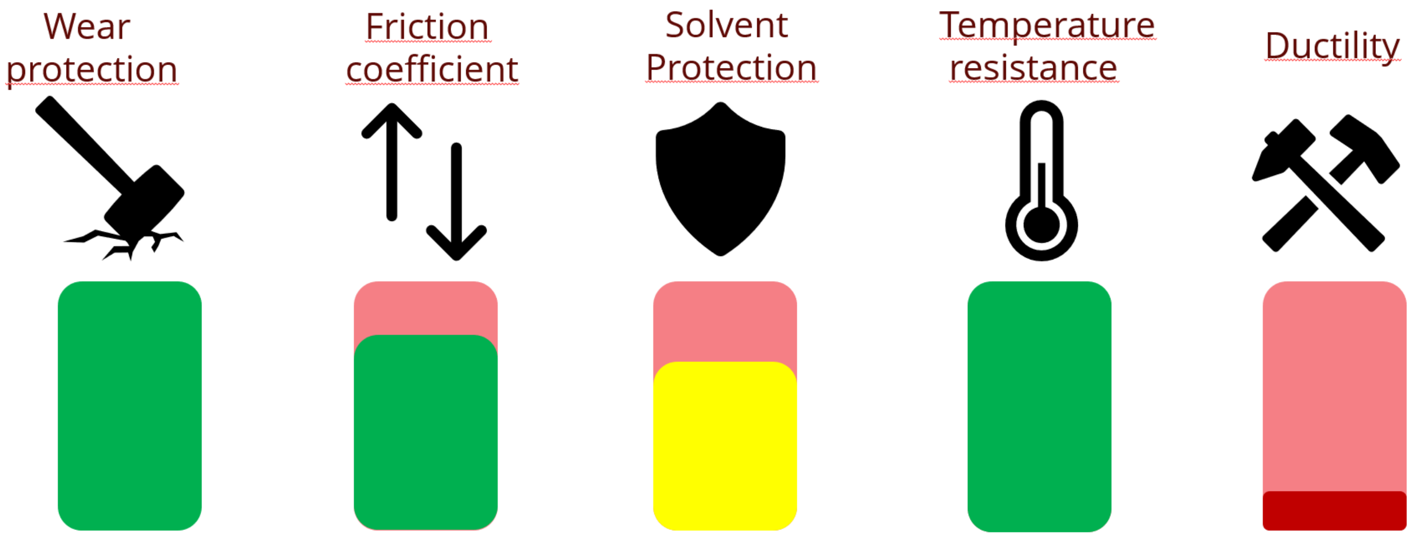


Why implementing PFAS alternatives is so difficult

- And how we fix it

Emil Damgaard-Møller, PhD, Senior consultant

edmo@teknologisk.dk; +45 7220 1626

"80% of all PFASs can be easily replaced by existing technologies/materials
- If time and money were no issue"

Quote: Emil Damgaard-Møller
Source: Experience and gut-feel

About me

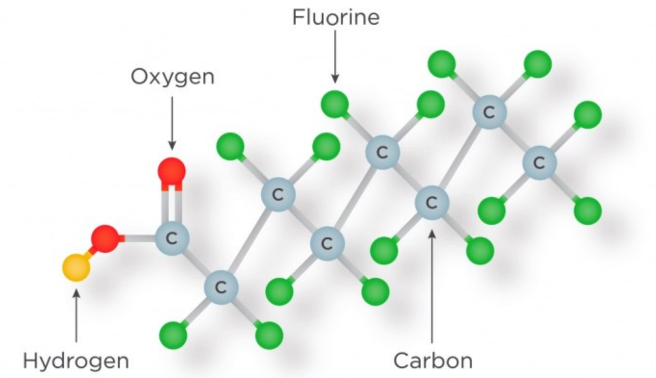
Emil Damgaard-Møller

AARHUS UNIVERSITET

PhD in materials chemistry

DANISH TECHNOLOGICAL INSTITUTE

Since Q1 2021

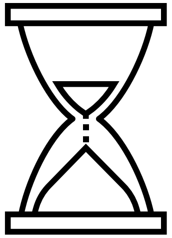


PFAS

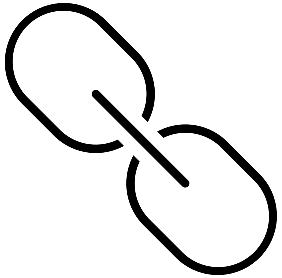
Recycling of wind turbine blades

Chemical detective work

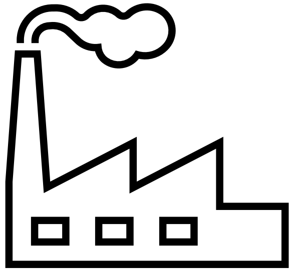
Setting the scene



PFAS is a legacy product



Supply chains are not transparent

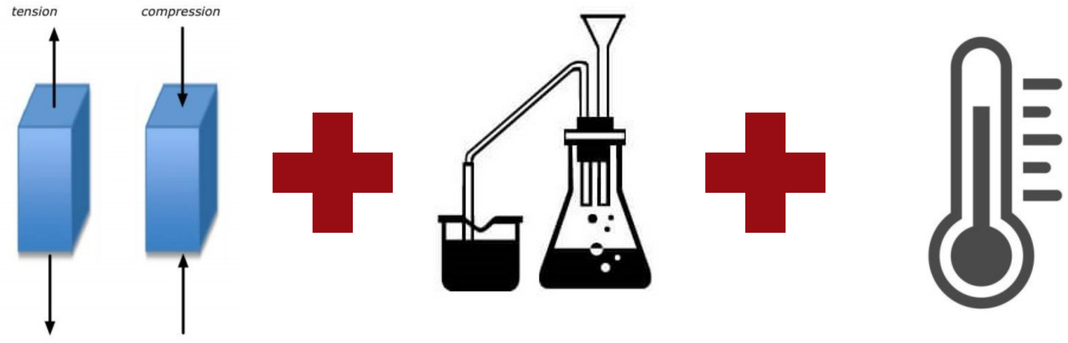


Companies have different types of PFAS issues

My focus: Fluoropolymers

Products are often over-engineered

Literature is very sparse on substitutes to fluoropolymers



No one-size-fits-all solution

The fluoropolymers exhibit good mechanical properties, chemical resistance and thermal properties. We have found no alternatives that are good on all three parameters

Material highlights

Polyketones (PEEK, PEK, PEKK)

Polyphenylene sulfide (PPS)

Polyamide imide (PAI)

Metals

Graphite

Polysulfones (PESU, PPSU, PSU)

Polyimide (PI)

Polymethylpentene (PMP)

Polypropylene (PP)

Polyethylene (PE, HD-PE, UHMW-PE, PE-LDD etc.)

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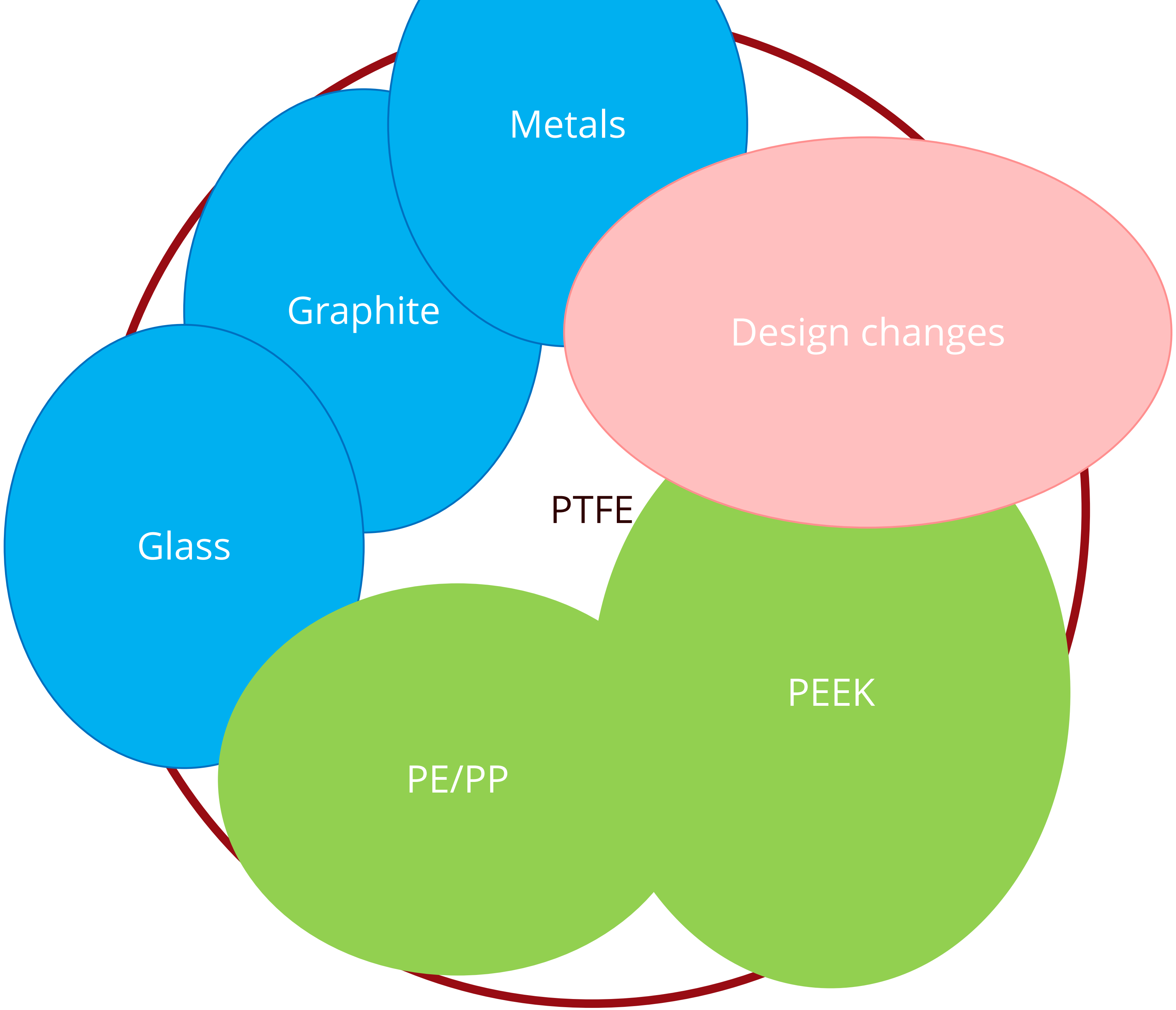

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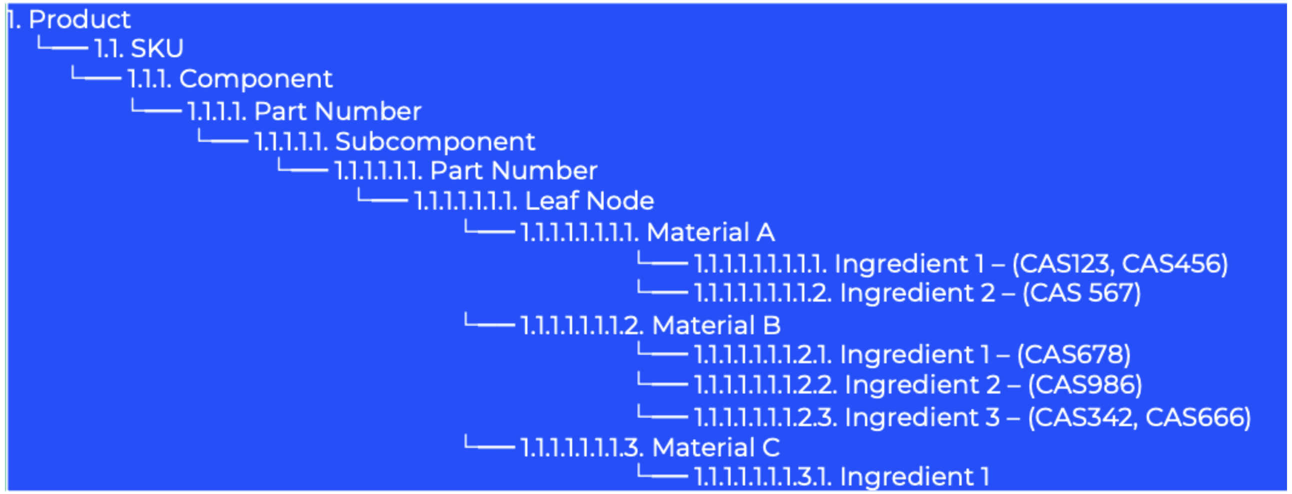
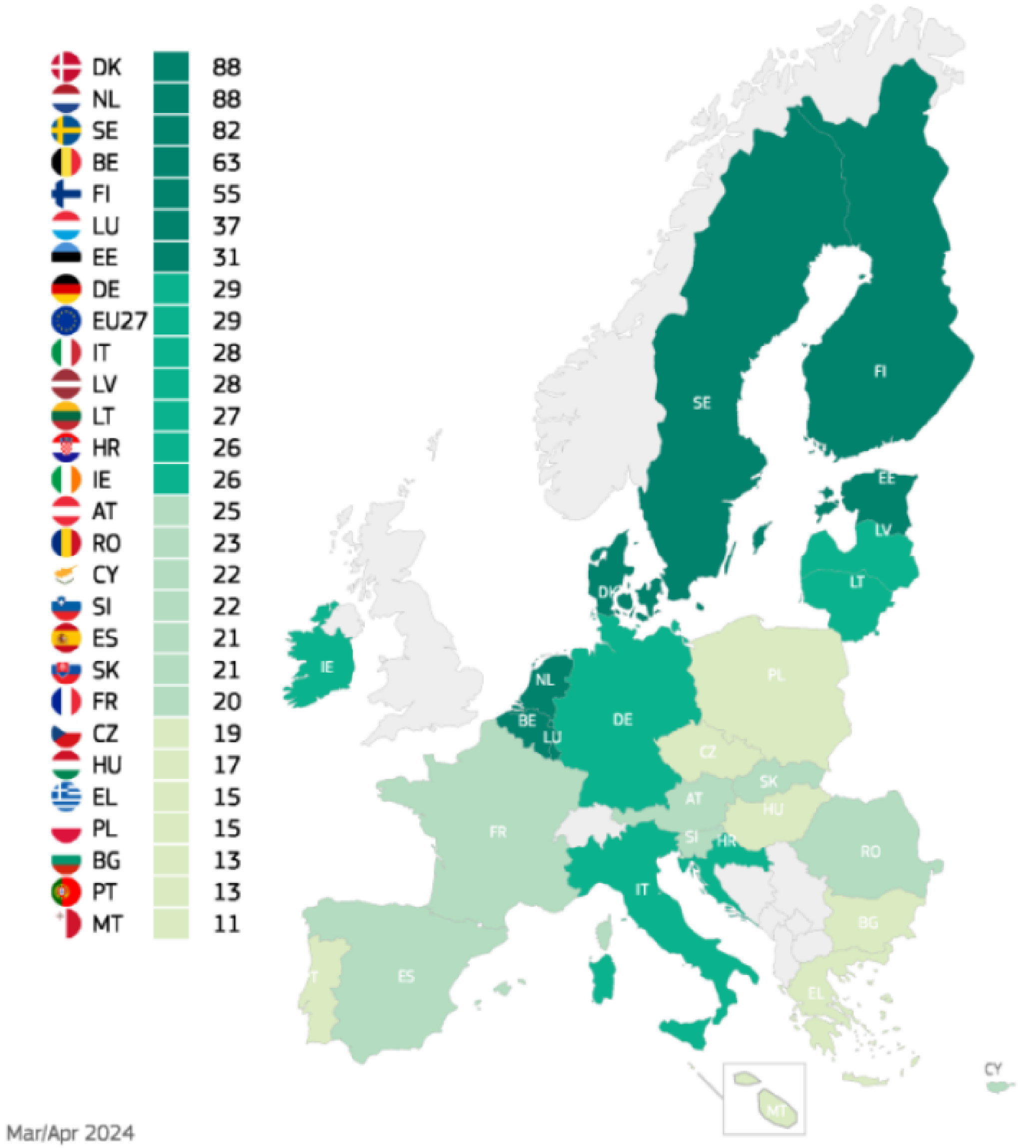
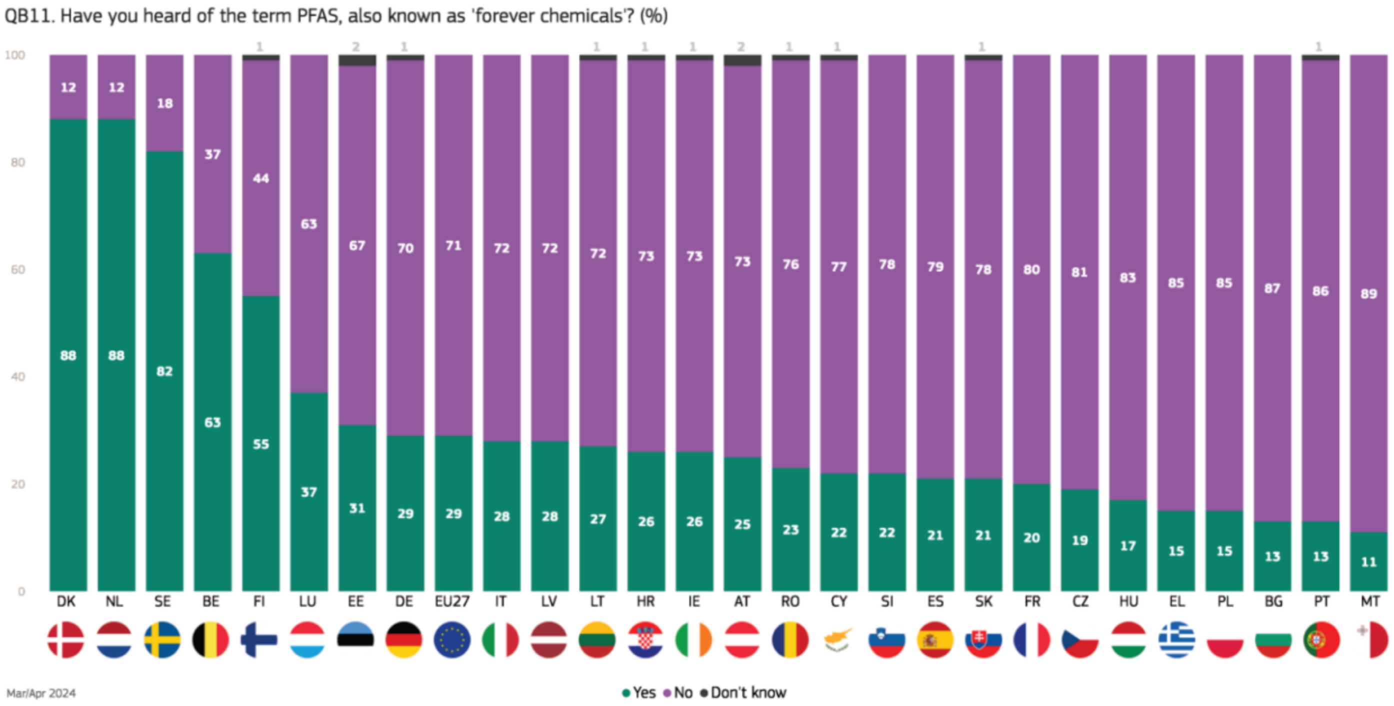
Transparency of supply chains

- Complex products and supply chains
- Understanding of PFAS is limited outside the EU
- 60-70% of all the information is already available for the companies, but the manual labor is too extensive
- Don’t know which suppliers to contact, so we contact them all
- Low reply rate from suppliers



Awareness of PFAS in EU

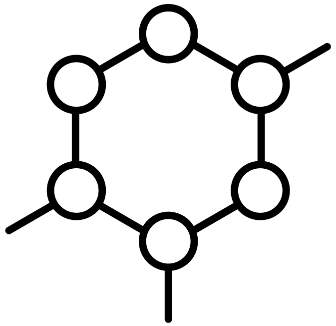




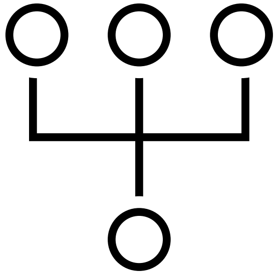
31 - 100
26 - 30
20 - 25
0 - 19

Source: https://europa.eu/eurobarometer/surveys/detail/3173

The different type of issues

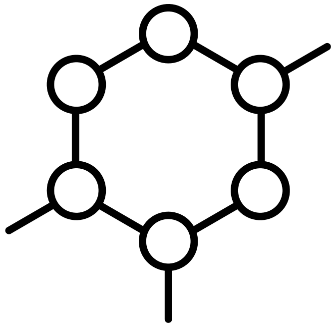


Using PFAS for a *property*



Using PFAS for its *diversity*

The different type of issues

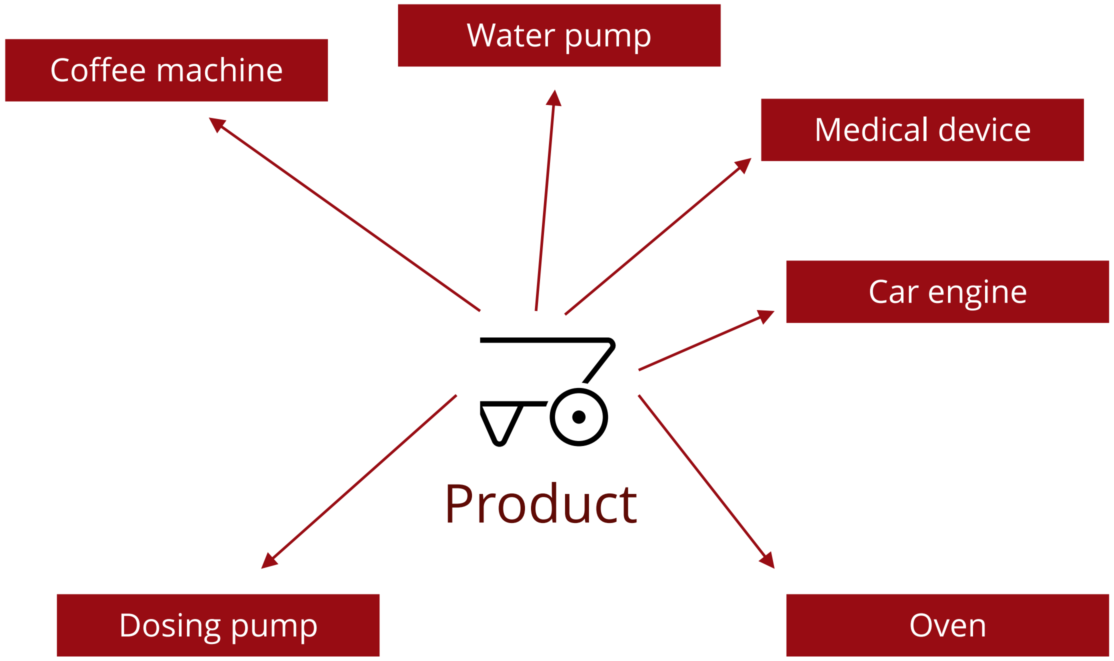


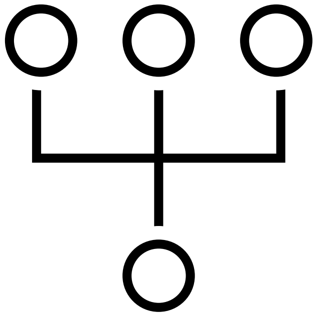
Using PFAS for a
property

Examples

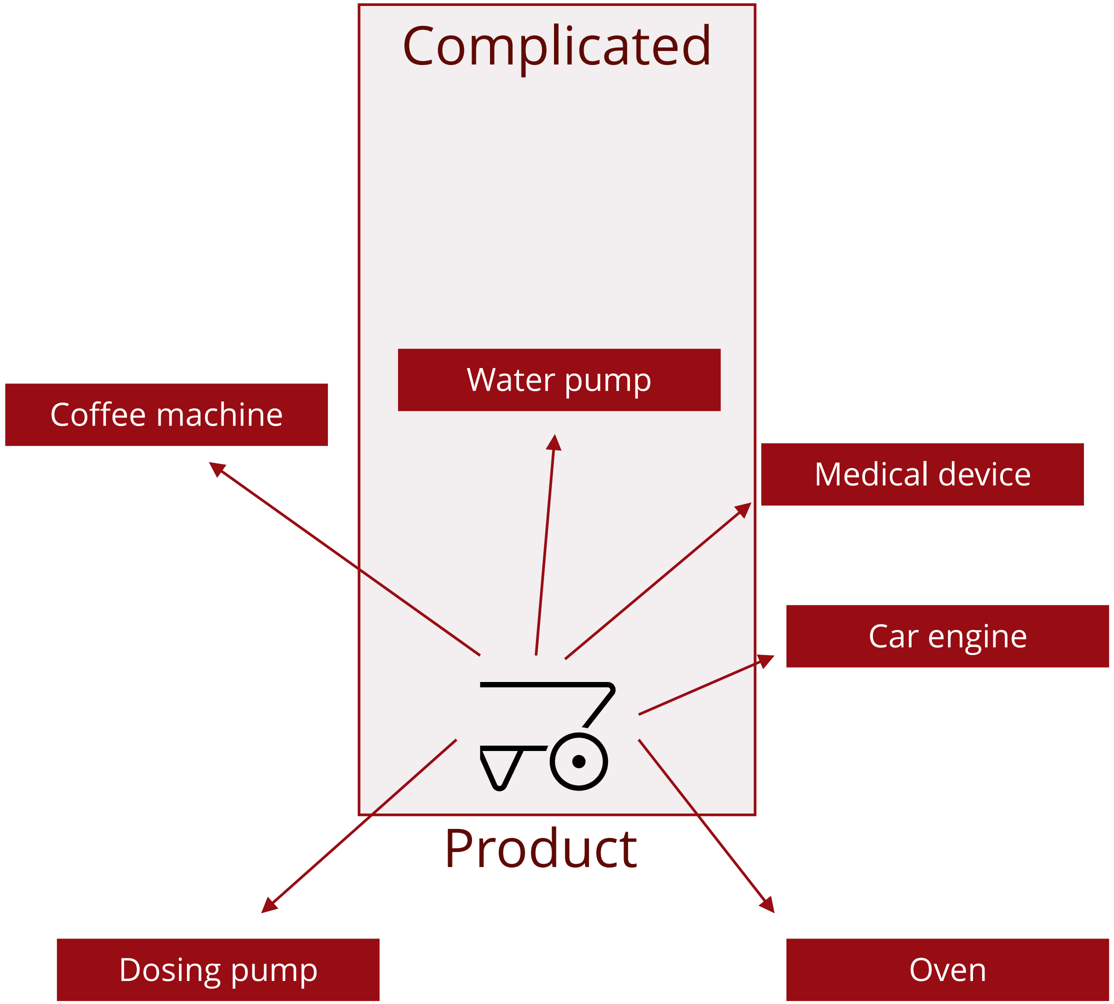
- Textile impregnation
- Anti-foaming agent
- Non-stick properties

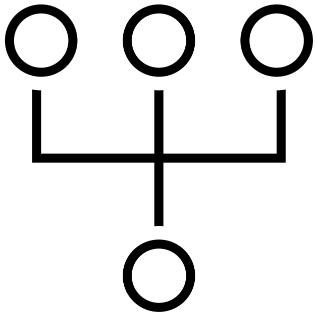
The different type of issues



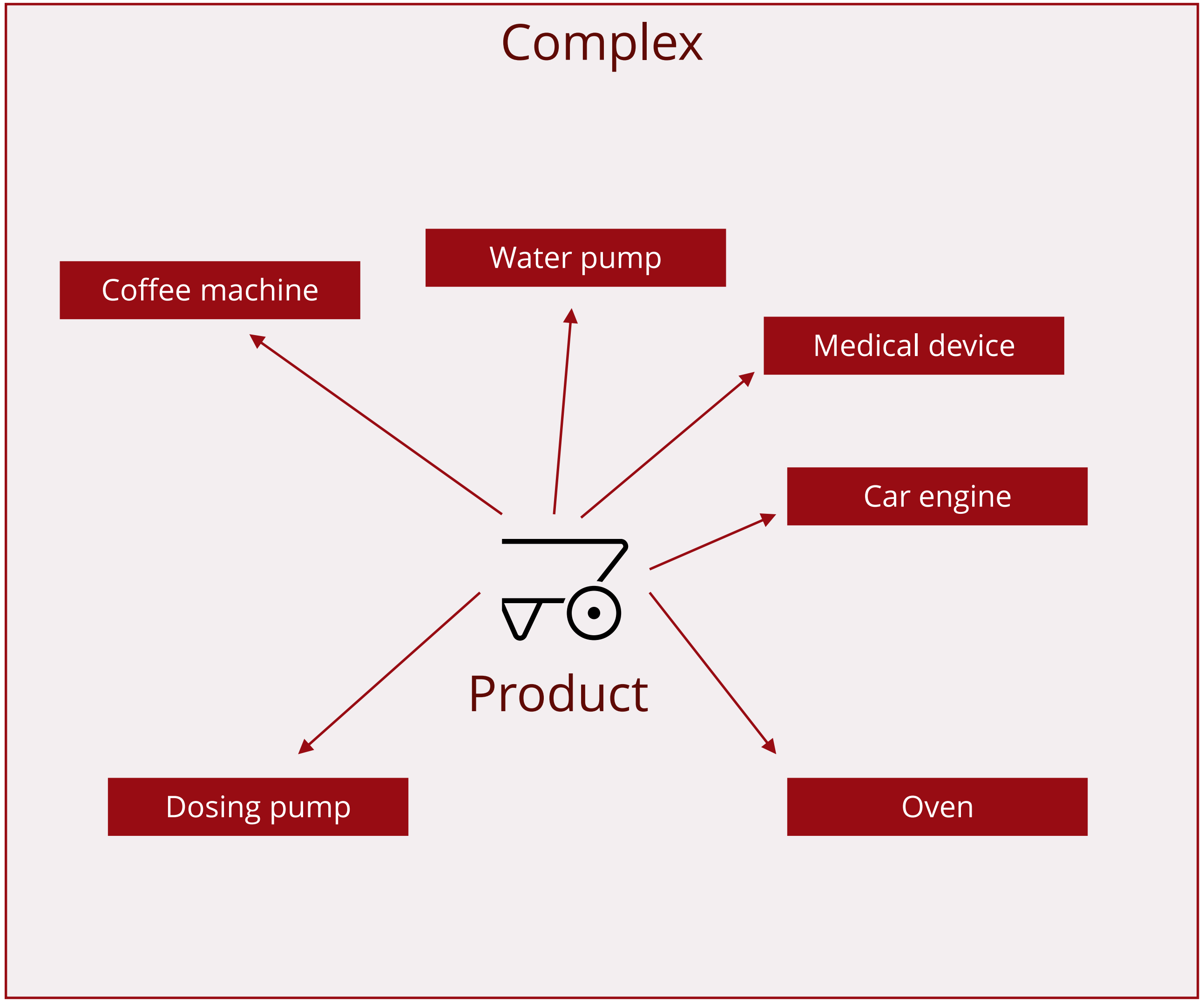


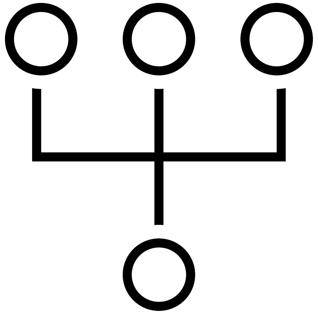
Using PFAS for its *diversity*





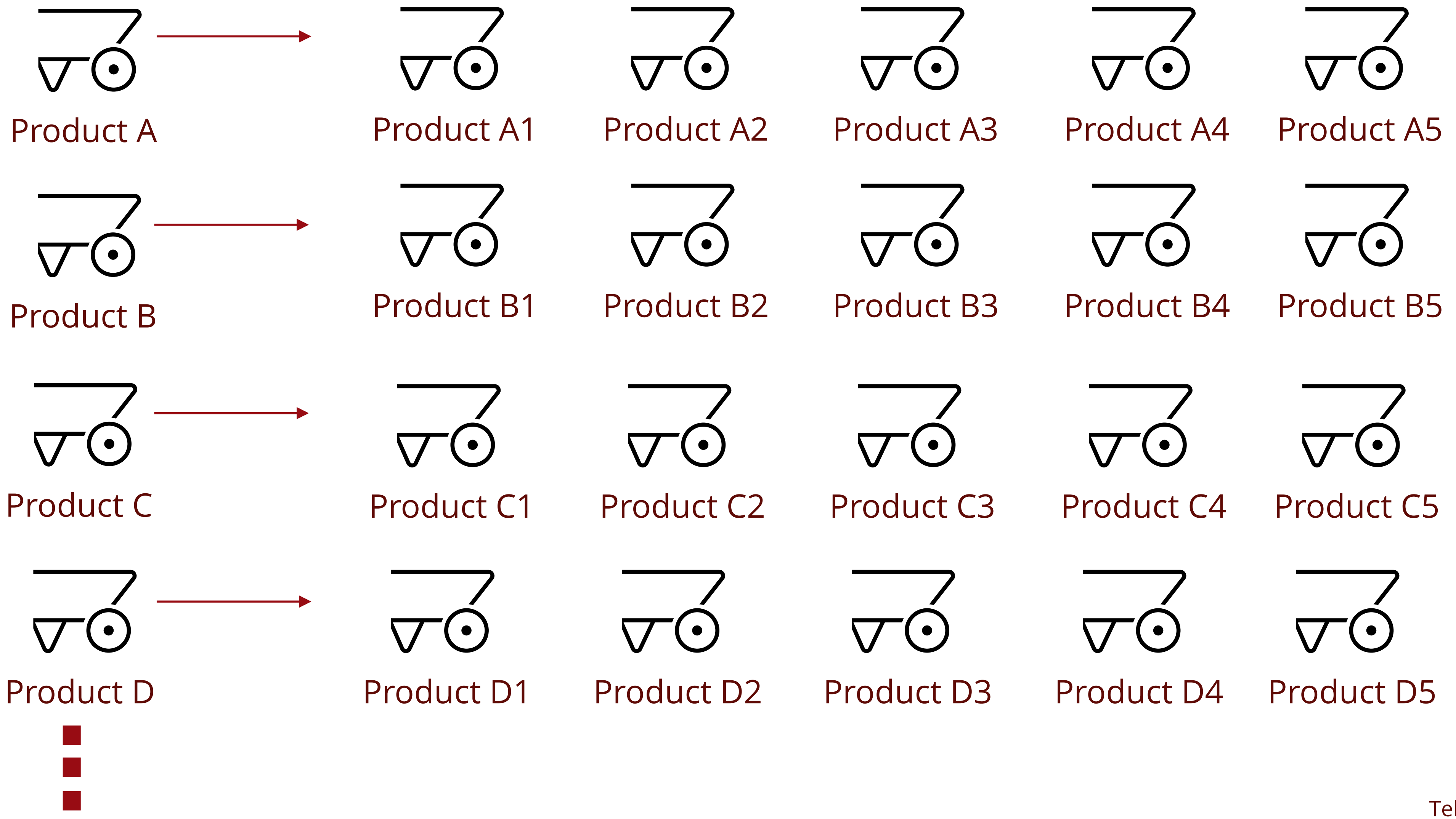
Using PFAS for its *diversity*



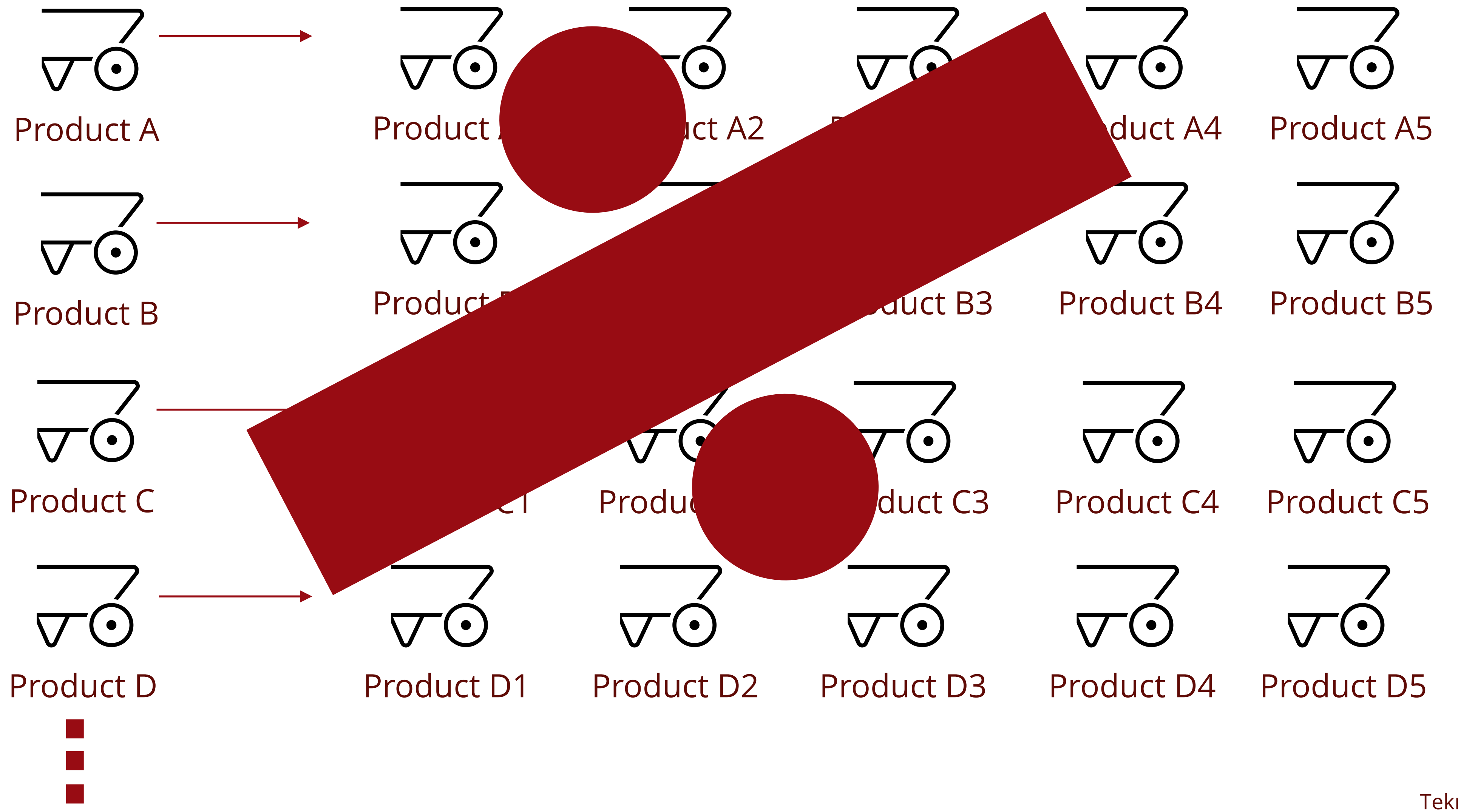


Using PFAS for its *diversity*

The different type of issues



The different type of issues



Summary

There is not going to be a 1:1 substitution to PFAS/fluoropolymers in general

We need to identify groups of uses, where a 1:1 substitution is possible

For example

- Heat + low friction
- Organic solvents + heat
- Non-stick + foodgrade + heat
- Low friction + harsh disinfecting agents

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Emil Damgaard-Møller

Kemisk konsulent ved Teknologisk Institut | PFAS | Cirkularitet | RCA | Materialekemi | Spektroskopi | Epoxy | Kompositter | Problemløsning | Plastik |

Snakker om #chemistry, #circularity, #problemsolving og #greentransition

Århus, Midtjylland, Danmark · Kontaktoplysninger

Teknologisk Institut

Aarhus Universitet

Let us keep in touch!

Thank you for your attention

PFAS & ALTERNATIVES

Yes - alternatives are available and viable

chemsec
INTERNATIONAL CHEMICAL SECRETARIAT

Jonatan Kleimark - ChemSec - RSC event – Feb 6, 2025

CHEMSEC TOOLS

chemsec SIN LIST

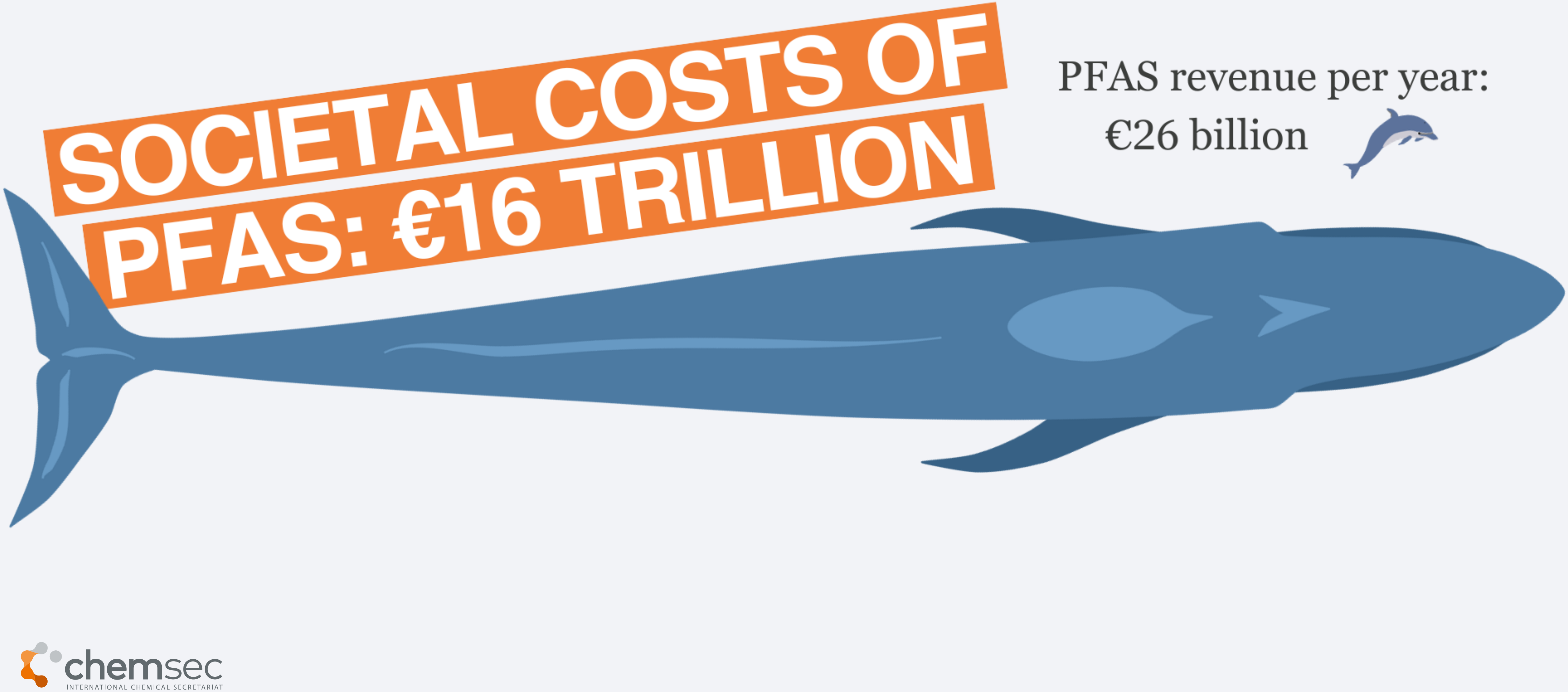
chemsec CHEMSCORE

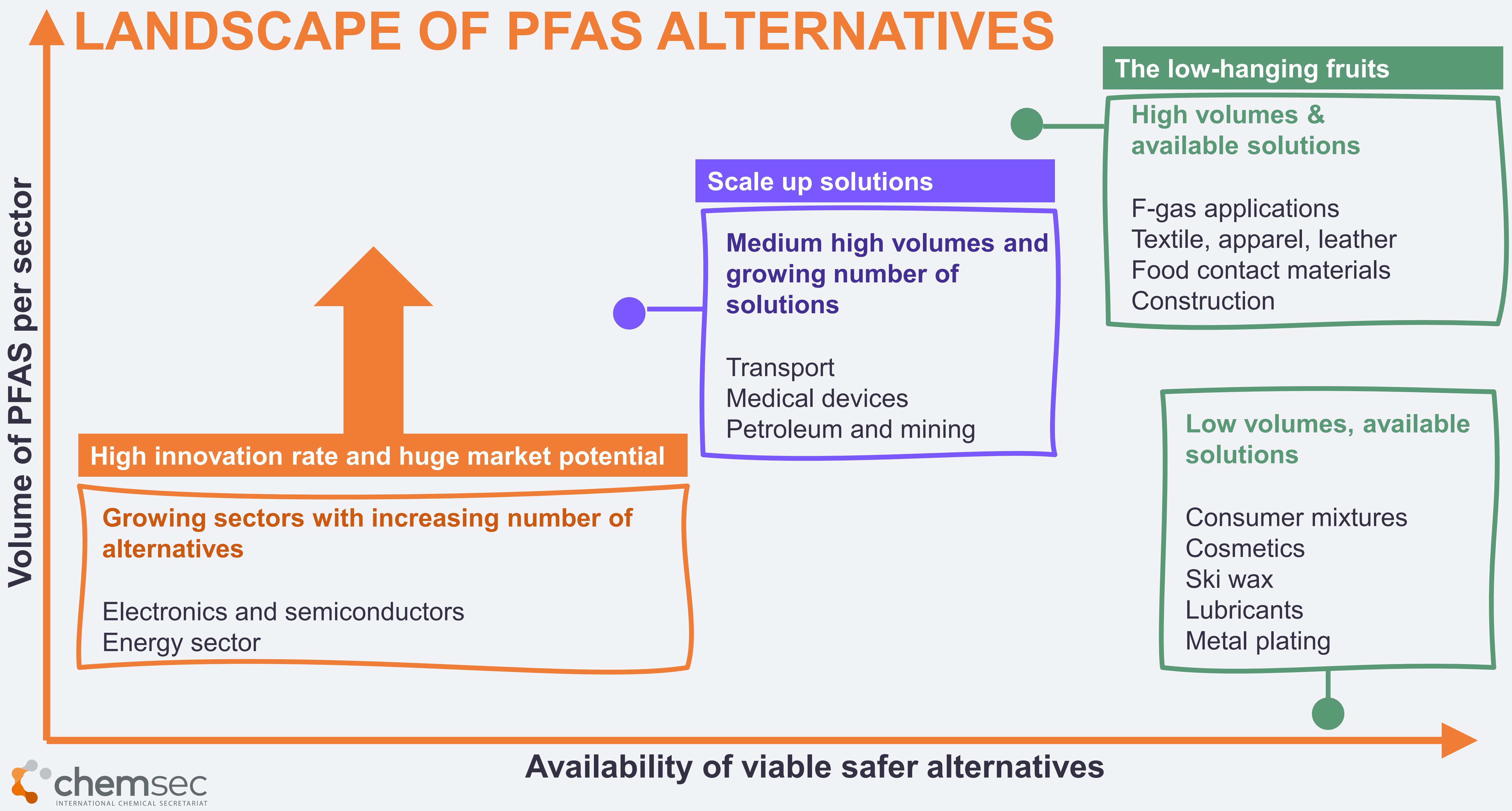
chemsec PFAS GUIDE

chemsec MARKETPLACE

chemsec SIN PRODUCERS

The ChemSec tools are part of the ZeroPM project and have been co-funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036756


SOCIETAL COSTS OF
PFAS: €16 TRILLION
PFAS revenue per year:
€26 billion
chemsec
INTERNATIONAL CHEMICAL SECRETARIAT


LANDSCAPE OF PFAS ALTERNATIVES
Volume of PFAS per sector
Availability of viable safer alternatives
High innovation rate and huge market potential
Growing sectors with increasing number of alternatives
Electronics and semiconductors
Energy sector
Scale up solutions
Medium high volumes and growing number of solutions
Transport
Medical devices
Petroleum and mining
The low-hanging fruits
High volumes & available solutions
F-gas applications
Textile, apparel, leather
Food contact materials
Construction
Low volumes, available solutions
Consumer mixtures
Cosmetics
Ski wax
Lubricants
Metal plating
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THE PFAS PHASE-OUT CHALLENGE

- Understanding PFAS impact on products and processess is a challenge
- Fashion/textile
- Consumer electronics
- Automotive – air conditioning

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PHASE-OUT IS HAPPENING

- Many sectors have viable alternatives on the market for example:
  - TULAC
  - Food packaging
  - Cosmetics
  - Ski wax
- Market transition requires legislation
- Legislation ensure ROI for early movers

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THANK YOU.

STAY IN TOUCH WITH CHEMSEC

- Website: chemsec.org
- Email: info@chemsec.org
- Newsletter: Sign-up page
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The ChemSec tools are part of the ZeroPM project and have been co-funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036756

HENRY ROYCE INSTITUTE

Henry Royce Institute

Prof. Ian Kinloch
Chief Scientific Officer

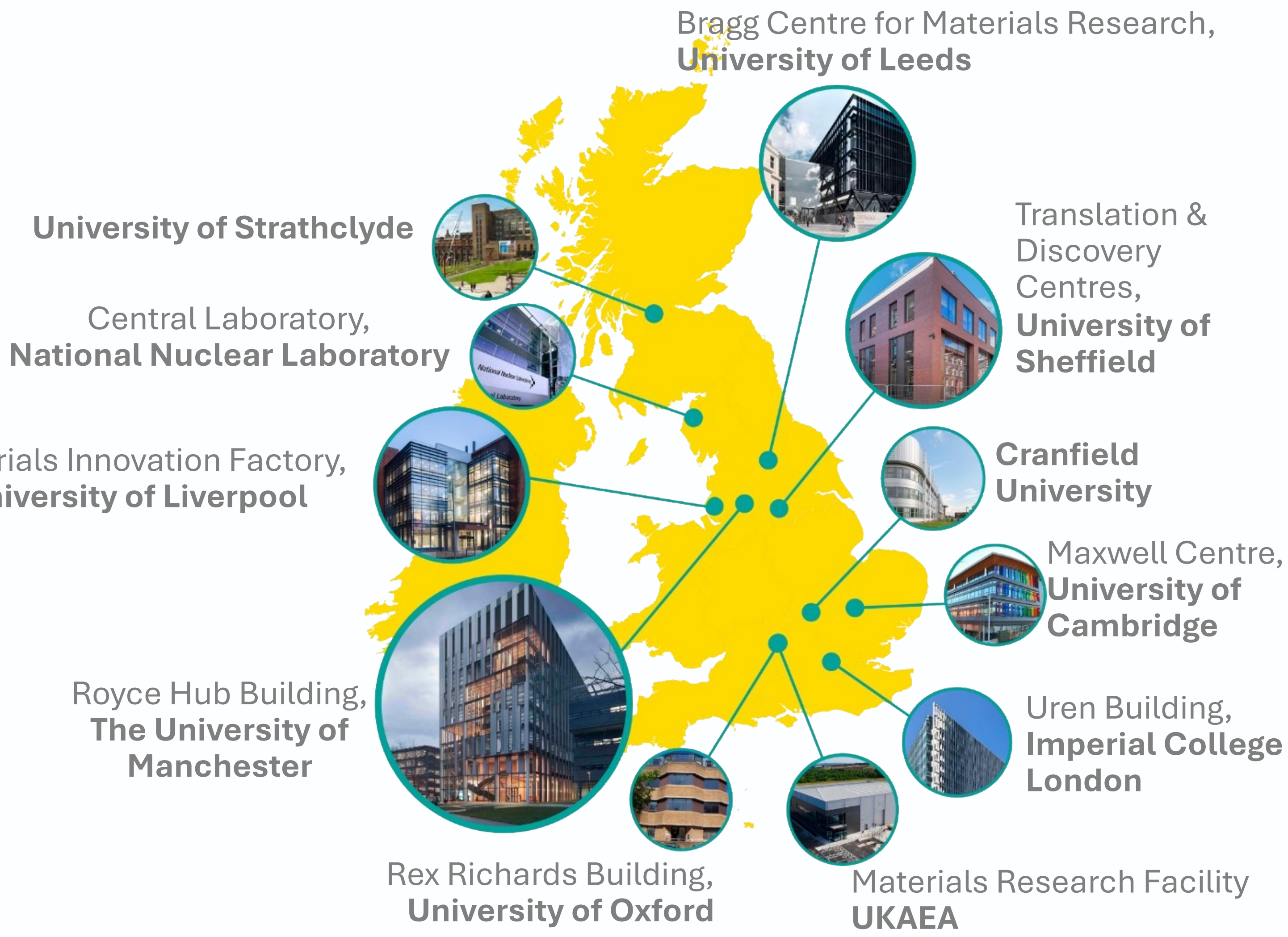
ROYCE

Royce - National institute with regional footprint

Founded in 2016, major EPSRC investment

The Henry Royce Institute was established to develop and capitalise on the UK's world-leading excellence in advanced materials research.

Royce supports and grows world-recognised excellence in UK materials research, accelerating commercial exploitation, and delivering positive economic and societal impact for the UK.



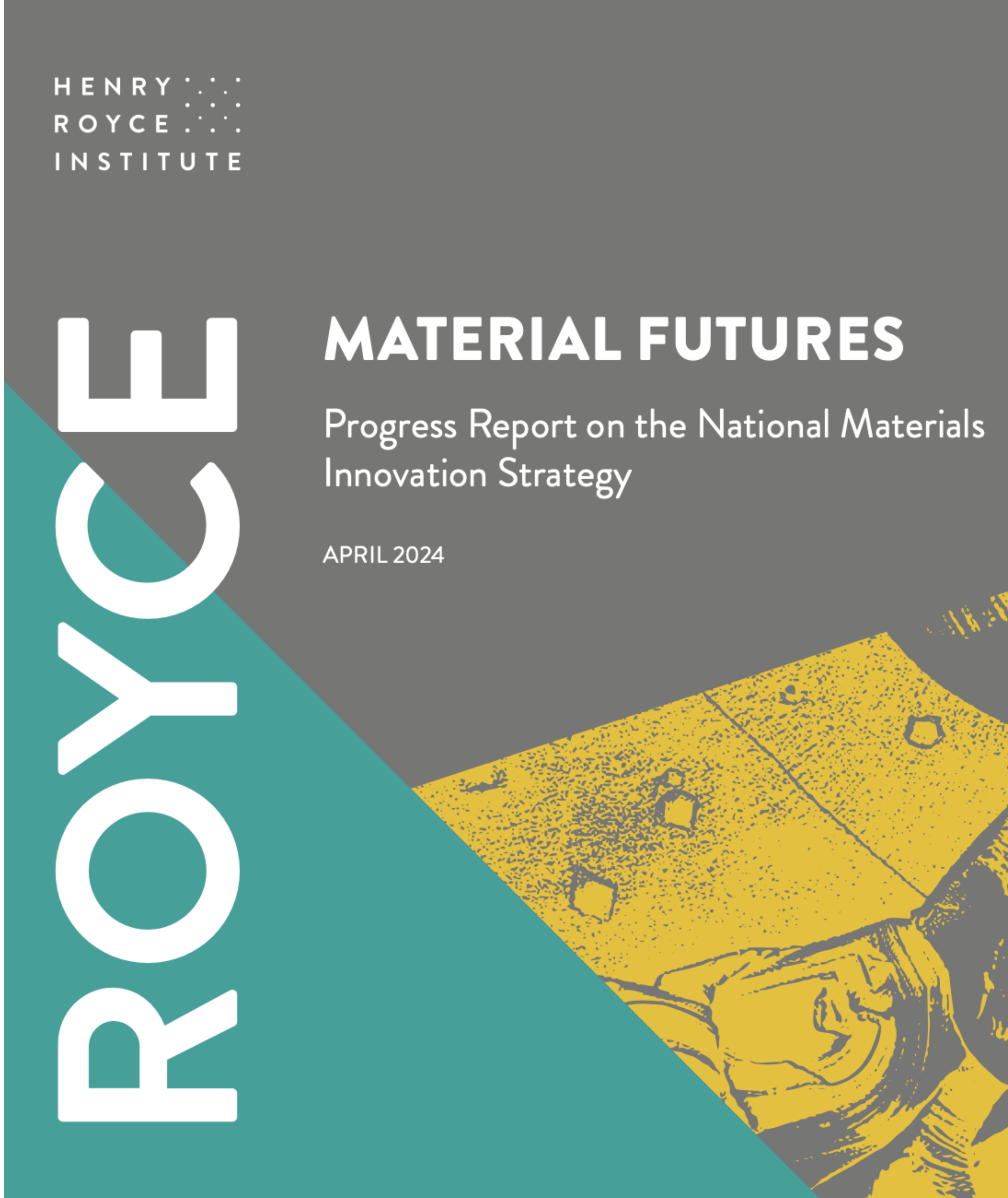
ROYCE

Royce Mission Pillars

- Enabling national materials research foresighting, collaboration and strategy
- Catalysing industrial collaboration and exploitation of materials research
- Providing access to the latest facilities and capability
- Fostering materials science skills development, innovation, training and outreach

National Materials Innovation Strategy

- Led by Materials Innovation Leadership Group
  - Top-down approach - National and industrial priorities
  - Focus on high impact application and process developments
  - Addressing technical and non-technical interventions
  - Identifying critical capabilities in materials innovation
- Materials Futures – Progress Report
- Expert Working Groups
  - 36x Materials EWGs – examples include:
    - EWG8 – Sustainable Packaging
    - EWG19 - Extreme Environments
    - EWG22/23 - Corrosion, Surface Protection & Tribology



MATERIALS INNOVATION CREATES JOBS, GROWTH AND OUTCOMES THROUGHOUT THE UK'S REGIONS

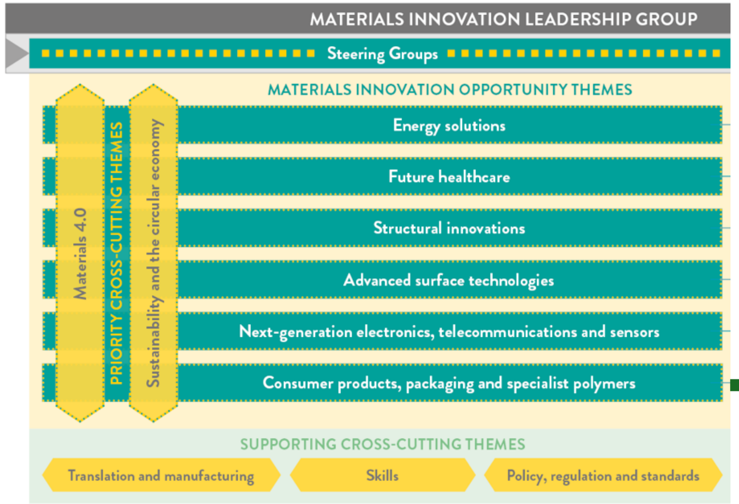
IMPLEMENTATION PLAN

PFAS In the National Materials Strategy

- Multiple sectors have raised the issue of PFAS restrictions or bans as a major concern, but they also present a global opportunity.

- PFAS-replacement materials will be considered within each NMIS opportunity theme. This falls under the “Sustainability” cross-cutting theme, which will be considered and responded to within each focus area.

PFAS In the National Materials Strategy



1. **Consumer goods**

2. **Sustainable Elastomers**

- The Global industry is projected to reach a value of £165 billion by 2030
- UK elastomer market size is between £1.6 and £2.4 billion
- UK sector is driven by automotive, medical, packaging, consumer goods, and aerospace

Sector Challenges/Opportunities

Specialist Elastomers:

- Development of new high-value specialist elastomeric materials for specialist applications **(including replacement of PFAS elastomers)**

High-volume elastomers:

- The biggest challenge is managing more than 50,000 tonnes of waste p.a.

Example Translational Activities

MATcelerate ZERO

ROYCE HYDROGEN ACCELERATOR

SUSTAINABLE MATERIALS INNOVATION HUB

FISC
Foundation Industries Sustainability Consortium

DMEx
Defence Materials Centre of Excellence

UKRI Analysis for Innovators

CEAMS Centre of Expertise in Advanced Materials and Sustainability

INDUSTRIAL COLLABORATION PROGRAMME

Mats4.0

Strategies for PFAS: Replace, Develop new materials, Remove and mitigate

Alternatives to Fluoropolymers - CRP

- Corrosion Resistant Products (CRP) utilise fluoropolymers in their piping products.
- The expected European PFAS ban is a serious commercial challenge.
- Through the CEAMS programme, CRP collaborated with Royce to identify alternative materials that could be used to replace PTFE and PFA usage in their production line.
- Crucially, the alternatives identified do not require significant capital outlay.
- By accessing Royce's expertise, CRP are now able to streamline their research and development decisions and are planning trials into alternative materials.

A4i Project: Sustainable single-use washbowls

Dr. Tom McDonald

Vernacare Washbowls are derived from plant fibres and are an environmentally friendly and biodegradable alternative to plastic

To marry with Vernacare's core values we are in search of a solution that maintains performance and patient dignity whilst reducing the environmental impact of the product.

The washbowls must provide a suitable receptacle for a warm water and detergent mix to allow for bed bathing patients within healthcare environments

Currently a C6 fluorocarbon is used to provide the detergent proofing, and 100's of alternatives have been tried with little success

Vernacare

SUSTAINABLE MATERIALS INNOVATION HUB

MANCHESTER 1824 The University of Manchester

Identify suitable techniques for characterisation of washbowls and wettability performance

Determine chemical composition and microstructure of the washbowls

Assess detergent stability variations depending on additives selected for study

Suggest suitable alternatives through assessment of supplied alternatives and by an in-depth literature review of current strategies

Alternative additive identified through SEM, NMR, contact angle and survivability testing.

Vernacare have made the decision to launch a PFAS free washbowl as a new product

Production trials to allow design validation started last week

Once launched further work will be conducted to reduce the addition rate, and / or find other alternative chemistries with our new knowledge.

Vernacare

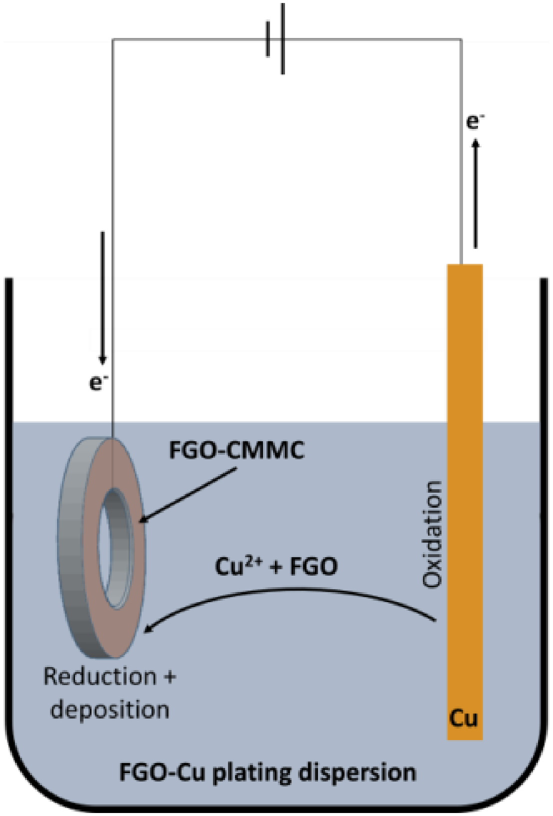
SUSTAINABLE MATERIALS INNOVATION HUB

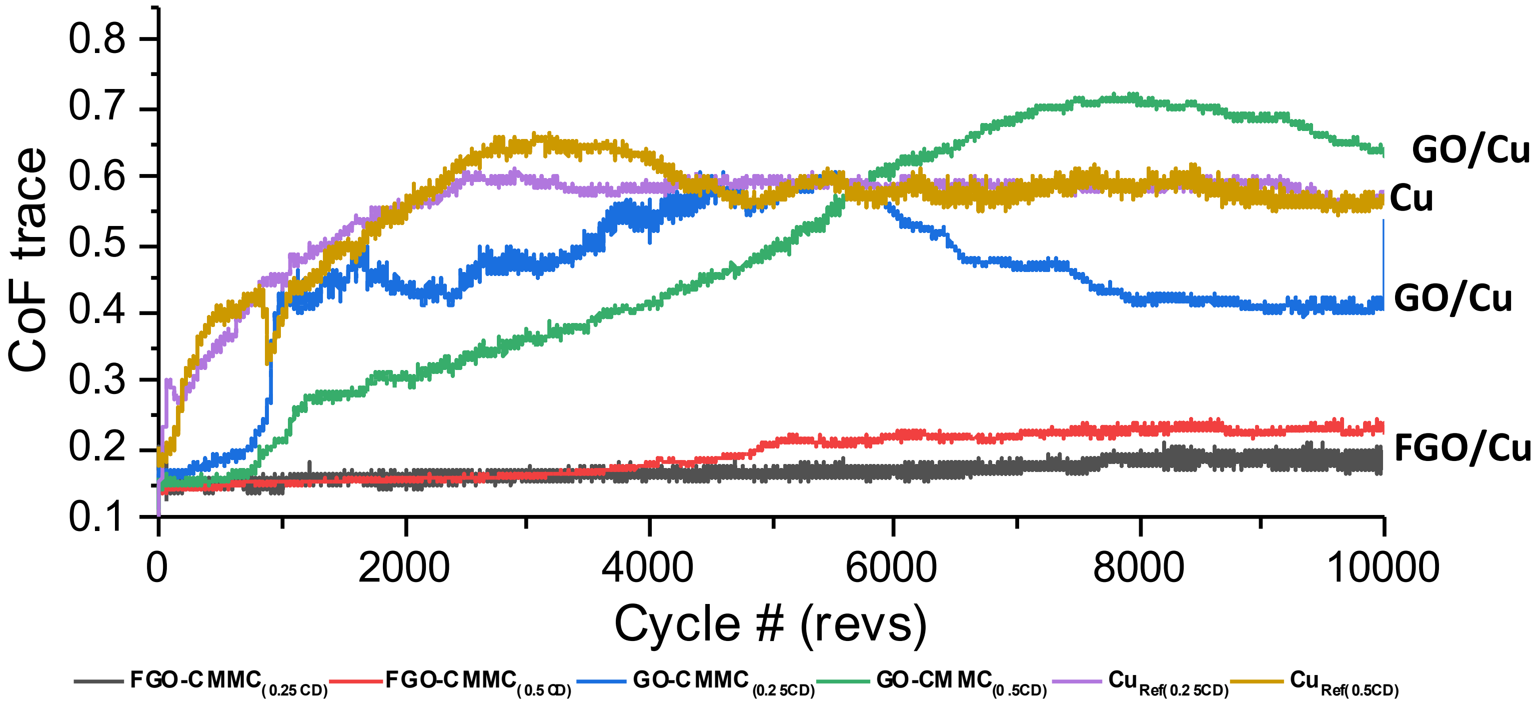
MANCHESTER 1824 The University of Manchester

New materials: Fluorinated coating

GRAPHENE FLAGSHIP

HENRY ROYCE INSTITUTE





FGO: Plasma fluorinated GO

((Mercadillo et al 2023 2D Mater. 10 025018)

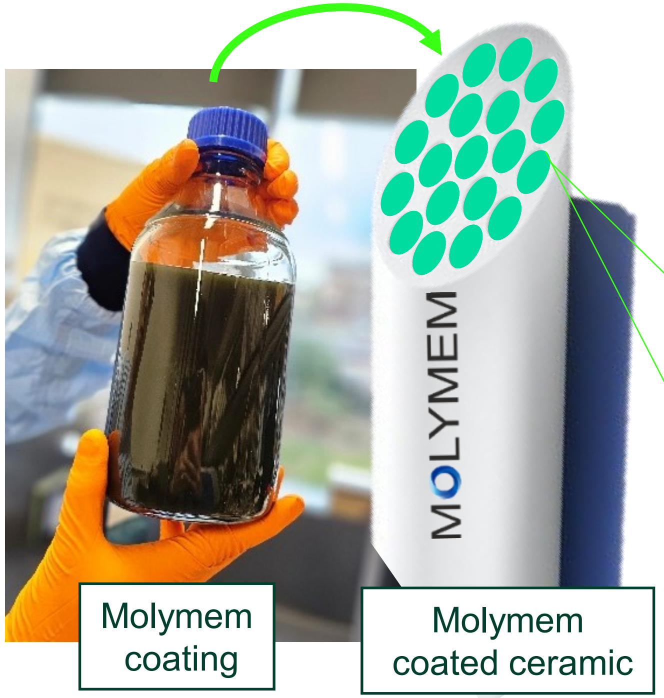
GO: Graphene oxide

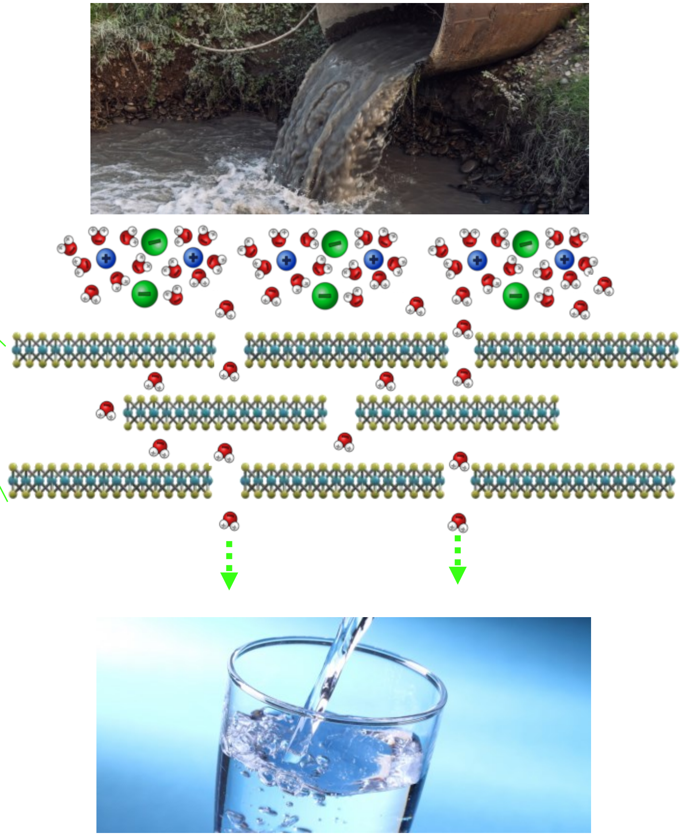
Material	C_{1s}	O_{1s}	N_{1s}	F_{1s}
GO	76.6 (±0.4)	22.6 (±0.8)	0.8 (±1.2)	0.0
FGO	68.4 (±1.0)	20.2 (±0.5)	0.7 (±1.1)	10.8 (±0.9)

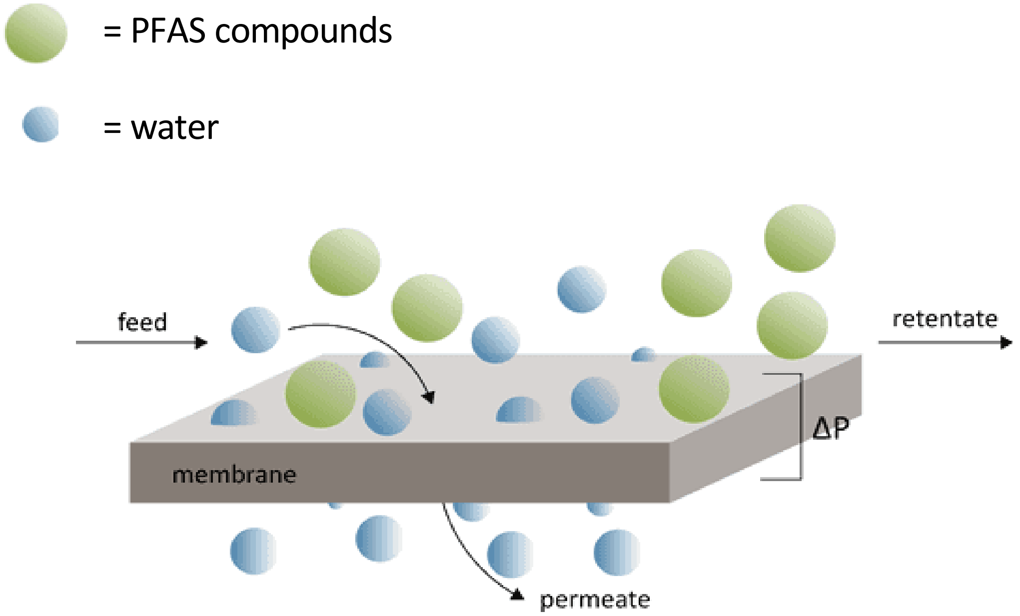
ACS Appl. Nano Mater. 2023, 6, 8202−8213

Removal: Molymem

MOLYMEM
Clean Water & Air







PFAS waters fed into the system; PFAS and other contaminants are rejected whilst water is collected

Developed a patented 2D nanomaterial additive that can be directly applied to the membrane surface to ***enable ceramic nanofiltration & protect polymer membranes***

CEAMS Centre of Expertise in Advanced Materials and Sustainability

PFAS Removal

Lead partner: Molymem Limited.
Consortium partners: Arvia Technologies

Academic support: Dr. Steven Boult & Prof. Bart Von Dongen (Earth & Environmental Sciences)

Spiked (simulated) PFAS containing waters → REMOVAL: Molymem ceramic NF membranes → DESTRUCTION: Arvia electrochemical technology

MANCHESTER 1824
The University of Manchester

MOLYMEM
Clean Water & Air

arvia

Summary

PFAS is recognized in the National Materials Strategy as a cross-sector challenge but particularly highlighted in the area of high performance, sustainable elastomers

Royce as national institute is working with other bodies in the UK to support industrial translation to solutions:

- Replace
- Develop new materials
- Remove and mitigate

ROYCE

AMI | Consulting

PFAS derived polymers and the opportunity for their replacement with alternate materials

RSC PFAS Workshop London February 2025

Presented by:
Richard Shepherd
Consultant AMI

AMI

The WHY

we help the plastics industry navigate, innovate and grow

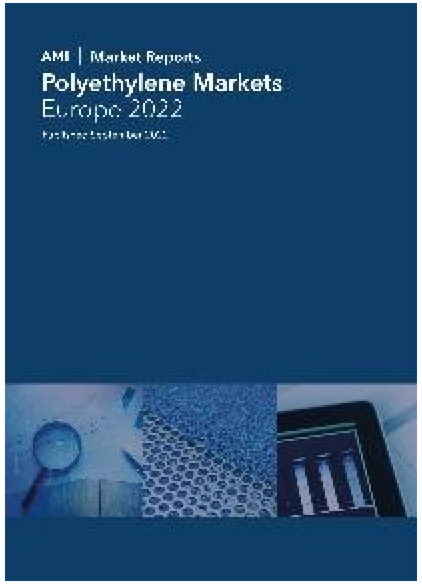
The HOW

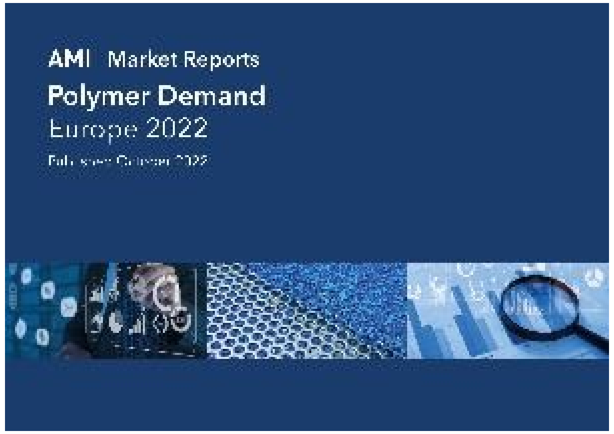
by providing business critical information and networking platforms

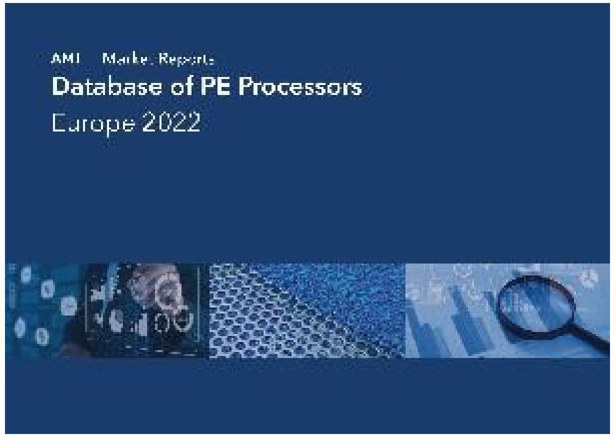
The WHAT

market intelligence products: consulting; events; digital-magazines

OUR CORE PRODUCTS







Plastics Processors in Europe, The Middle East and Africa

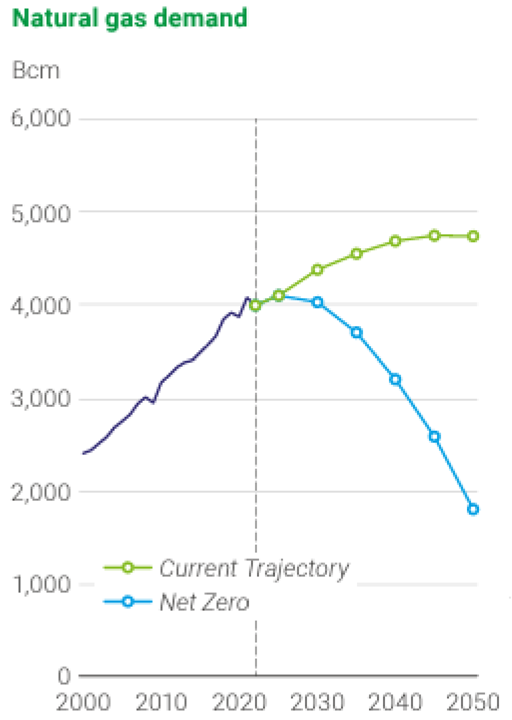
Background (brief)

- Per- and Polyfluoroalkyl Substances (PFAS) are a broad “Class” of materials under scrutiny for health and environmental concerns
- Certain EU member states are seeking to restrict the use of PFAS and the placing on the market of products containing PFAS in the EU as far as possible
- Additionally REACH scope for proposed PFAS regulation includes both small molecules **and** polymers
- When REACH was originally developed, requesting registration for polymers was deemed too difficult, because of the complexity of the polymer market

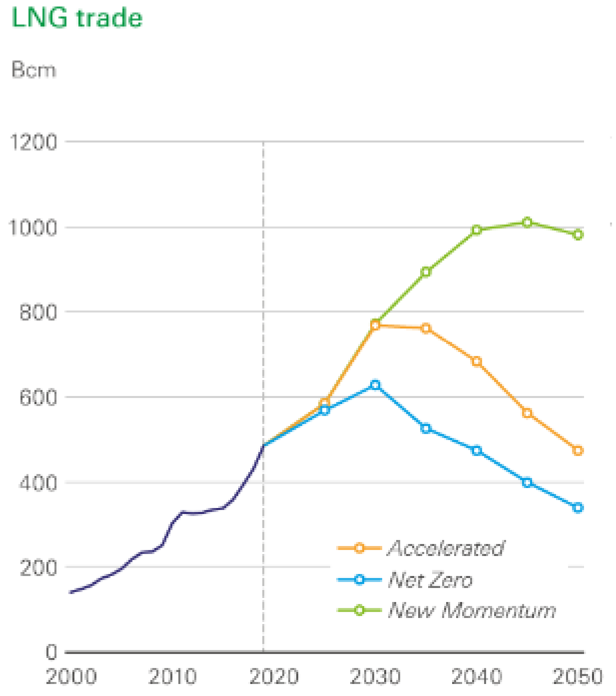
- Polymeric PFAS, or fluoropolymers, are used as coatings for non-stick cookware, as water repellent textiles, and in electronic equipment
- In the sealing industry fluoropolymers include fluoroplastics such as PTFE which are used in gaskets, and cross-linked fluoroelastomers (rubbers) with application as O-rings and custom geometry seals
- Such PFAS polymers are considered to be Polymers of low Concern in the sealing industry
- As such they pose no concern to public safety, yet the current REACH definition of PFAS groups these polymers together with low molecular weight PFAS of known concern such as PFOA and PFOS

The (potential) impact of PFAS regulation in the Energy Sector – considering the market for hydrocarbons specifically

Prospects for natural gas depend on the speed of the energy transition



LNG trade increases in the near term, with the outlook becoming more uncertain post 2030

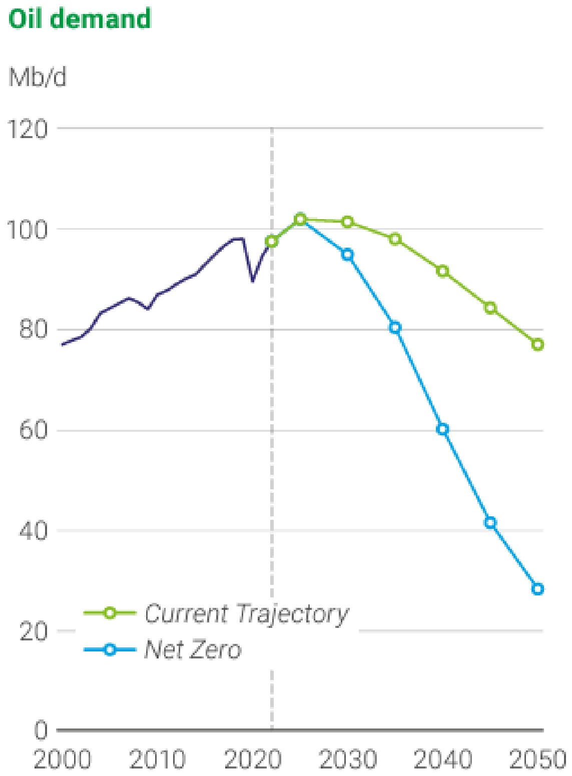


bp Energy Outlook: 2024 edition

bp-energy-outlook-2023
PDF (www.bp.com)

The (potential) impact of PFAS regulation in the Energy Sector – considering hydrocarbons specifically

Oil demand falls over the outlook as use in road transportation declines and gas replaces oil for power generation



bp Energy Outlook: 2024 edition

…unintended consequence?

Marine transport (in the Energy sector too)

- Typically ocean-going ships operate with oil-lubricated stern tubes and use lubricating oils in on-deck and underwater (submerged) machinery.
- In 2010 between 36.9 to 61 million liters of lubricant leaked into global marine waters from stern tube and operational discharge from shipping
- Mineral Oil was the preferred lubricant for global shipping, however, Mineral oil is harmful to aquatic and terrestrial ecosystems
- In 2013 the Vessel General Permit (VGP) from the Environmental Protection Agency (EPA) in the US mandated the use of Environmentally Acceptable Lubricants (EALs) in all oil-to-water interfaces for vessels 79 feet or longer that enter waters

- Traditional marine sealing materials (e.g., nitrile) designed for use with mineral oil are incompatible with Environmentally Acceptable Lubricants (EALS). They experience changes in mechanical properties, their volume, hardness and tensile strength can all change, resulting in seal failure
- Due to complexity in the supply chain and operational use sealing material must work with all types of EAL and be compatible with the cocktail of different bi-products. FKM Fluoroelastomers are the only seal material found to offer compatibility with all EAL type lubricants

To name just a few applications…

Elastomers

- Packer elements
- Cavity pumps
- Scrapers; discs/cups
- Flexible Joints
- Liners
- Bonded hoses
- Sealing systems
- Umbilicals

Thermoplastics

- Flexible pipe – flowlines jumpers etc
- Control lines
- Umbilicals

Why fluoropolymers?

	ELASTOMER											
	CI	EPDM	Nitrile			Fluorinated						
	CR		NBR	HNBR		FKM 1	FKM 2	FKM 3	FKM 5	FEPM		FFKM
FLUID			med ACN	low ACN	med ACN					Aflas	Extreme	
Crude oil	NO	NO	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Condensate	NO	NO	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Diesel	NO	NO	OK	NO	OK	OK	OK	OK	OK	OK	OK	OK
Aromatic HC solvents	NO	NO	NO	NO	NO	OK	OK	OK	OK	NO	NO	OK
Naphthenic HC solvents	NO	NO	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Aliphatic HC solvents	OK	NO	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
HC solvents, chlorinated	NO	NO	NO	OK	OK	OK	OK	OK	OK	NO	NO	OK
HC solvents, oxygenated	NO	NO	NO	NO	NO	NO	NO	NO	OK	NO	NO	OK
Hydraulic oil, mineral oil	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Hydraulic oil, approved synthetic	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Oil based mud	NO	NO	OK	NO	OK	OK	OK	OK	OK	OK	OK	OK
Ester based mud	?	NO	NO	NO	NO	NO	NO	NO	?	NO	NO	OK
Water; formation, injected, sea	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Steam	NO	OK	NO	OK	OK	NO	NO	NO	?	OK	OK	?
High pH aqueous	?	OK	OK	OK	OK	NO	NO	NO	NO	OK	OK	OK
Brine completion fluid pH>9	?	OK	OK	OK	OK	NO	NO	NO	NO	OK	OK	OK
Brine completion fluid pH<9	?	OK	?	OK	OK	?	?	?	OK	OK	OK	OK
Frac pack fluid	?	OK	OK	?	?	OK	NO	NO	OK	OK	OK	OK
Amine based inhibitors	?	OK	OK	?	?	NO	NO	NO	OK	OK	OK	?
Triazine	?	OK	OK	OK	OK	NO	NO	NO	?	OK	OK	OK
HCl acid	NO	OK	NO	NO	NO	OK	OK	OK	?	OK	OK	OK
HF/HCl	NO	OK	NO	NO	NO	NO	NO	OK	?	OK	OK	OK
Acetic acid, dilute	?	OK	NO	OK	OK	OK	OK	OK	?	?	OK	OK
Zinc bromide/chloride	?	OK	NO	NO	NO	OK	OK	OK	?	OK	?	OK
MEG, 100%	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
MEG/water	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
TEG, 100%	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Water glycol hydraulic fluid, pH <9	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Water glycol hydraulic fluid, pH >9	OK	OK	OK	OK	OK	NO	NO	NO	OK	OK	OK	OK
Methanol (dry)	OK	OK	OK	OK	OK	NO	OK	NO	OK	OK	OK	OK
Methanol, <97%	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Isopropanol, 100%	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
H_2S, dry gas	?	OK	NO	NO	NO	OK	OK	OK	OK	OK	OK	OK
Natural gas with condensate	NO	NO	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Carbon dioxide, gas	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK

Typical elastomer selection guide; material v's exposure fluids (Oil field bias!)

Selection driven by the end-user too

G General Guidance on Elastomer Compatibility

General Guidance on Elastomer Compatibility
This table indicates materials that are generally acceptable in the services shown but the use of this table is not a proper alternative to material selection per the body of this GP.

Material [1]	Examples of Common Name or Trade Name	Typical Useful Service Temperature Range °F (°C)	Inhibitor Chemicals [7]	Asphaltene Inhibitors [7]	Xylene, Toluene, and Other Aromatic Compounds	Resistance to RGD [2]	H_2S Service < 0.05 psi (0.003 bar) H_2S	H_2S Service > 0.05 psi (0.003 bar) H_2S	100% Methanol [3]	< 90% Methanol [3]	Steam	Brine Completion Fluid pH < 9	Brine Completion Fluid pH > 9	Calcium Bromide	Zinc Bromide or Zinc Chloride	Formates < 300 °F (150 °C)	Formates > 300 °F (150 °C)	Hydrochloric Acid	Oil-Based Mud	Ester-Based Mud
Fluoroelastomers (FKM)	Viton® A Viton® E60 Viton® A401C FKM 1	0 °F to 350 °F (−18 °C to +177 °C)	U [5]	U	A	Q	A	A	U	A	U	Q	U	A	A	U	U	A	Q	Q
	Viton® B FR 58/90 FKM 2	14 °F to 350 °F (−10 °C to +177 °C)	U [5]	U	A	Q	A	A	Q	A	U	Q	U	A	A	U	U	A	Q	U
	Viton® GF FKM 3	20 °F to 350 °F (7 °C to 177 °C)	U [5]	U	A	Q	A	A	A	A	U	Q	U	A	A	U	U	A	Q	Q
	Viton® GLT FR 25/90 FKM 3	−22 °F to +350 °F (−30 °C to +177 °C)	U [5]	U	A	Q	A	A	U	A	U	Q	U	A	A	U	U	A	Q	Q
	Viton® GFLT FKM 3 Fluoraz®	−10 °F to +350 °F (−23 °C to +177 °C)	U [5]	U	A	Q	A	A	A	A	U	Q	U	A	A	U	U	A	Q	Q
Perfluoro-elastomers (FFKM)	Kalrez® Chemraz® Parofluor®	0 °F to 450 °F (−18 °C to 232 °C)	A	Q	A	Q	A	A	A	A	Q	A	A	A	A	A	A	A	A	A

Key: A = Acceptable; Q = Qualification Required; U = Unacceptable

Why fluoropolymers?

Solubility parameter is king…

- Solubility parameters for a range of solvents and elastomers

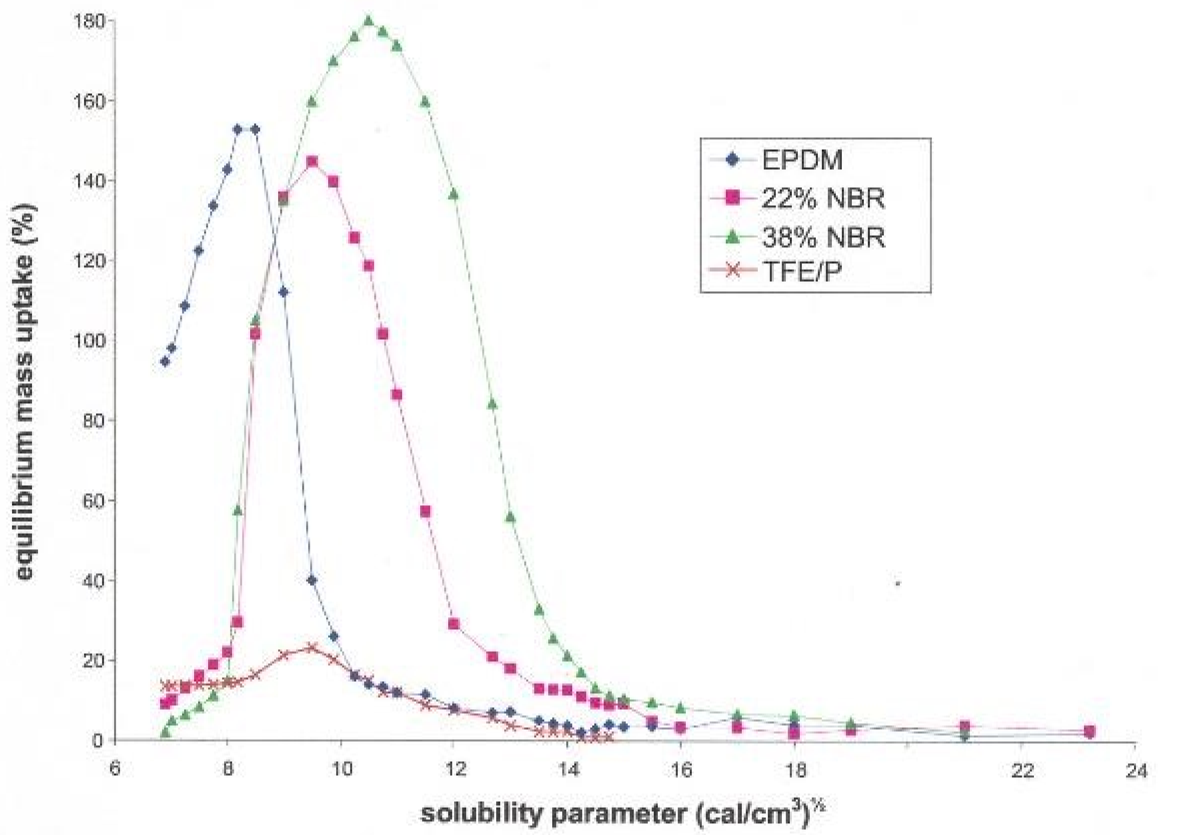
Solvent	δ^{a2}
iso-octane	6.90
hexane	7.33
octane	7.60
diethylether	7.74
decane	7.77
p-xylene	8.83
m-xylene	8.87

Solvent	δ^{a2}
Toluene	8.97
o-xylene	9.03
ethyl acetate	9.10
Benzene	9.22
MEK	9.56
Acetone	9.74
1,2-dichloroethane	9.96

Solvent	δ^{a2}
propanol	12.0
ethanol	12.9
methanol	14.5
ethylene glycol	14.5
water	23.2

Elastomer	δ^{a2}	δ range[a3]	Elastomer	δ^{a2}	δ range[2]
EPDM	8.25	7.5 - 9.0	ECO	10.7	9.0 - 12.5
FEPM	9.0	8.5 - 10.0	FKM I	10.9	9.0 - 12.5
LOW NBR	9.3	8.5 - 11.0	HIGH NBR	11.0	9.0 - 12.0
HNBR	9.6	8.5 - 11.5	FKM III		10.5 - 11.5
FKM II	10.7	9.0 - 12.0	FFKM		

*Swelling not measurable



So, we just replace fluoropolymers with something else?

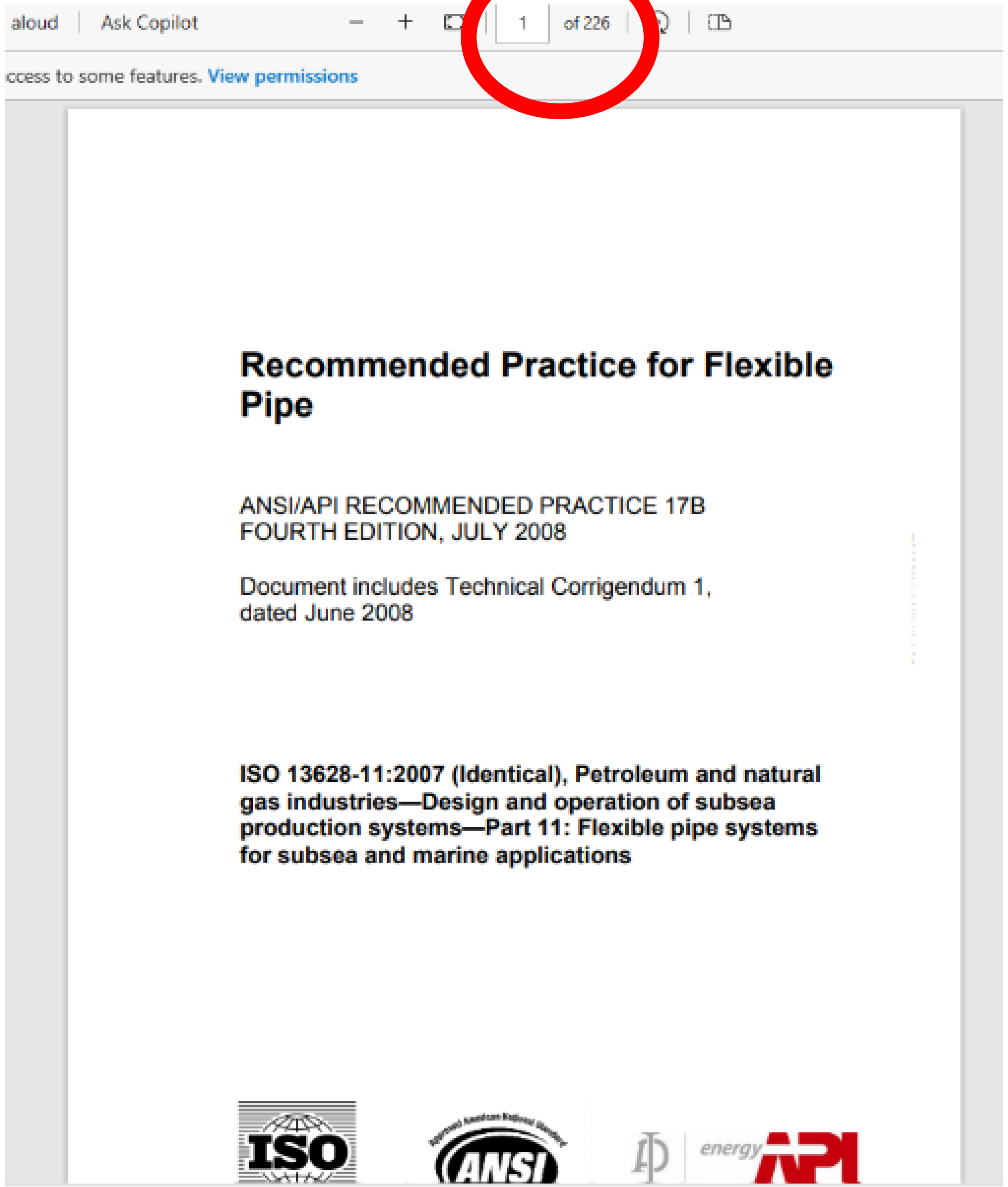
- Evolution of these materials has taken years of development
- Qualification programmes can take upwards of two years for seals and significantly longer for flexible pipe and the like
- Replacement will likely require a whole new generation of materials

- The use of low molecular weight PFAS raw materials is limited to the manufacturing locations of the fluoropolymer and fluoroelastomer
- A practicable solution might be that PFAS monomers in the polymer supply chain are exempted from any PFAS ban and that different controls are considered which enable their safe and continued use

	ELASTOMER											
	CI	EPDM	Nitrile			Fluorinated						
	CR		NBR	HNBR		FKM 1	FKM 2	FKM 3	FKM 5	FEPM		FFKM
FLUID			med ACN	low ACN	med ACN					Aflas	Extreme	
Crude oil	NO	NO	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Condensate	NO	NO	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Diesel	NO	NO	OK	NO	OK	OK	OK	OK	OK	OK	OK	OK
Aromatic HC solvents	NO	NO	NO	NO	NO	OK	OK	OK	OK	NO	NO	OK
Naphthenic HC solvents	NO	NO	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Aliphatic HC solvents	OK	NO	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
HC solvents, chlorinated	NO	NO	NO	OK	OK	OK	OK	OK	OK	NO	NO	OK
HC solvents, oxygenated	NO	NO	NO	NO	NO	NO	NO	NO	OK	NO	NO	OK
Hydraulic oil, mineral oil	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Hydraulic oil, approved synthetic	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Oil based mud	NO	NO	OK	NO	OK	OK	OK	OK	OK	OK	OK	OK
Ester based mud	?	NO	NO	NO	NO	NO	NO	NO	?	NO	NO	OK
Water; formation, injected, sea	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Steam	NO	OK	NO	OK	OK	NO	NO	NO	?	OK	OK	?
High pH aqueous	?	OK	OK	OK	OK	NO	NO	NO	NO	OK	OK	OK
Brine completion fluid pH>9	?	OK	OK	OK	OK	NO	NO	NO	NO	OK	OK	OK
Brine completion fluid pH<9	?	OK	?	OK	OK	?	?	?	OK	OK	OK	OK
Frac pack fluid	?	OK	OK	?	?	OK	NO	NO	OK	OK	OK	OK
Amine based inhibitors	?	OK	OK	?	?	NO	NO	NO	OK	OK	OK	?
Triazine	?	OK	OK	OK	OK	NO	NO	NO	?	OK	OK	OK
HCl acid	NO	OK	NO	NO	NO	OK	OK	OK	?	OK	OK	OK
HF/HCl	NO	OK	NO	NO	NO	NO	NO	OK	?	OK	OK	OK
Acetic acid, dilute	?	OK	NO	OK	OK	OK	OK	OK	?	?	OK	OK
Zinc bromide/chloride	?	OK	NO	NO	NO	OK	OK	OK	?	OK	?	OK
MEG, 100%	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
MEG/water	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
TEG, 100%	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Water glycol hydraulic fluid, pH <S	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Water glycol hydraulic fluid, pH >S	OK	OK	OK	OK	OK	NO	NO	NO	OK	OK	OK	OK
Methanol (dry)	OK	OK	OK	OK	OK	NO	OK	NO	OK	OK	OK	OK
Methanol, <97%	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Isopropanol, 100%	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
H_2S, dry gas	?	OK	NO	NO	NO	OK	OK	OK	OK	OK	OK	OK
Natural gas with condensate	NO	NO	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Carbon dioxide, gas	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK

So, we just replace fluoropolymers with something else?

Qualification of flexible pipe can take many years requiring test samples from dumbbell size to full scale (production representative) lengths of pipe



Recommended Practice for Flexible Pipe

ANSI/API RECOMMENDED PRACTICE 17B
FOURTH EDITION, JULY 2008

Document includes Technical Corrigendum 1, dated June 2008

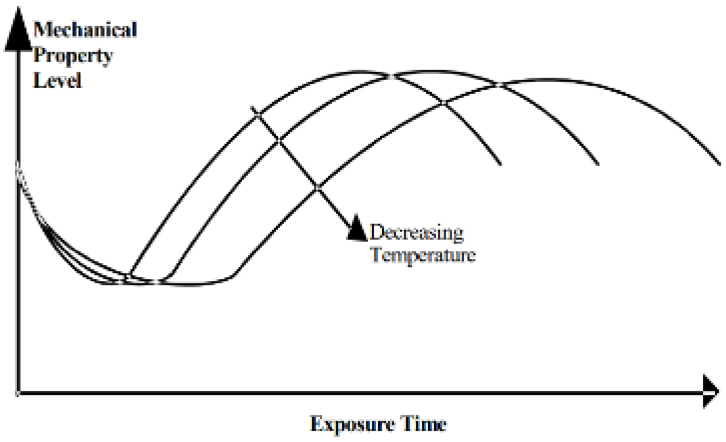
ISO 13628-11:2007 (Identical), Petroleum and natural gas industries—Design and operation of subsea production systems—Part 11: Flexible pipe systems for subsea and marine applications

And for the more humble o-ring..?

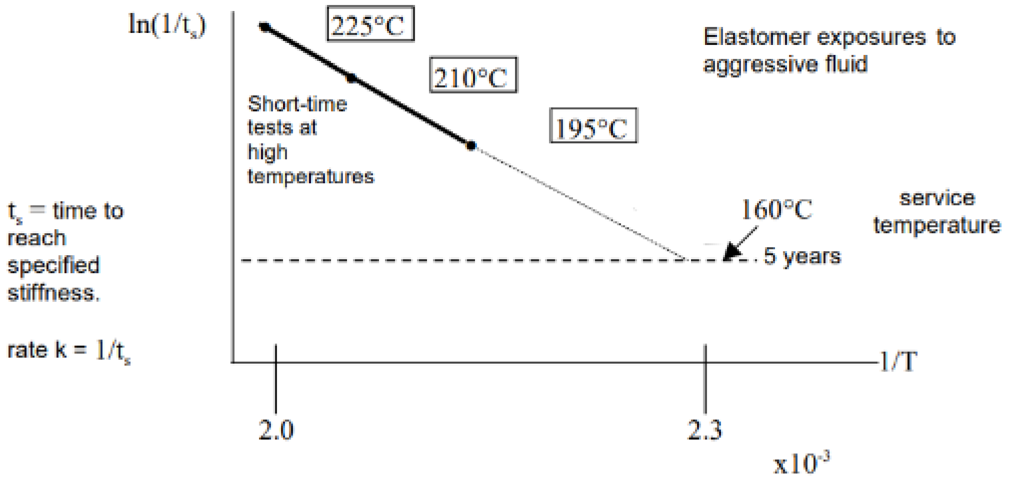
Typical project life expectation >25 years

- Arrhenius ageing techniques can be used
- A relevant (say mechanical) property is selected and measured at (minimum) 3 temperatures
- Exposure time noted to reach a selected property % at each temperature

- Technique is complicated by the fact that these are often materials for high temperature applications so accelerated ageing may not be appropriate
- Secondary (non-relevant) failure modes may be introduced



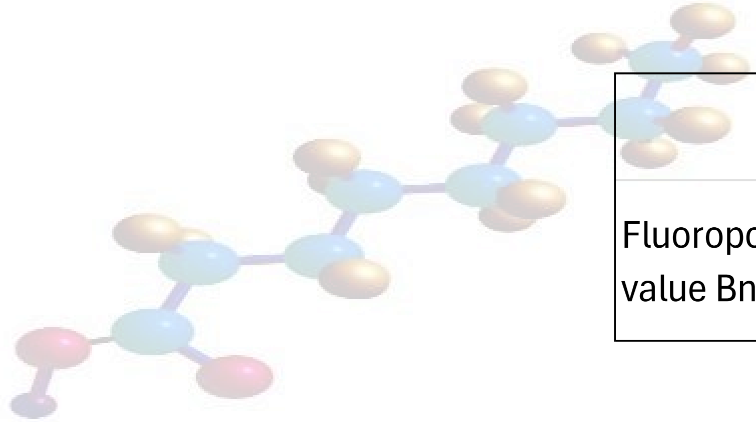
Changes in e.g. modulus level versus exposure time at three temperatures



Extrapolation to service temperature using an Arrhenius plot

End uses/users/market value

		Transportation		Health care		Chemical		Consumer			Telecommunications			Infrastructure	Renewable energy		
		Auto	Aero	Pharma	Medical devices	Oil and gas	Chemical process industry (CPI)	Production of goods	Protection and packaging	Filtration	Electronics and semiconductors	Internet and wireless coms	Technical textiles	Construction and architecture	Energy production	Hydrogen production	Energy storage
PVDF	Polyvinylidene fluoride	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
PVDF	polyvinylidene fluoride	•	•	•	•		•	•	•	•	•	•	•	•		•	•
ECTFE	Ethylene-chlorotrifluoroethylene	•	•	•		•	•				•	•		•			
ECTFE	Ethylene-chlorotrifluoroethylene			•		•	•										
PCTFE	Polychlorotrifluoroethylene		•	•							•						
FEVE	Fluoroethylene-vinyl ether	•	•								•			•			
EFEP	Ethylene-tetrafluoroethylene- hexafluoropropylene	•			•		•				•						
CPT	Chlorotrifluoroethylene- tetrafluoroethylene	•									•						
THV	TFE-HFP-VF2	•	•	•			•	•	•	•	•			•	•		•
FEPM	Trifluoroethylene-propylene copolymer	•	•	•	•	•	•	•			•			•	•		
FKM	HFP-VF2 polymer and HFP-VF2-TFE polymers	•	•	•	•	•	•	•	•		•		•	•	•	•	•
FFKM	TFE-PMVE perfluoroelastomer		•	•	•	•	•	•			•						



	2023		2033
Fluoropolymer market value Bn(USD)	$ 8.38	→	$ 13.90

Conclusions

- PFAS (derived materials) are seen as critical to global industry in their use as sealing elements
- Fluoroelastomer seals are *currently* the only option available for many applications, however…
- End users have a part to play – with risk aversion leading to over specification
- Other materials are available and may be suitable but will require qualification
- This process needs to start **now** to have viable alternatives and a more rapid “transition”
- Transport of Liquefied Natural Gas require sealing materials that can withstand the hydrogen disulphide and/or extreme low temperature applications yet retain excellent fugitive emission performance.
- Fluoroplastics such as PTFE retain sealing compliance at cryogenic temperature because of their extremely low glass transition temperature. PTFE lip seals for cryogenic valves, and PTFE gaskets for cryogenic storage tankers are essential

AMI | Consulting

Thank you!

If you have any questions, please contact:

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PEEK & PAEK POLYMERS: SUSTAINABLE HIGH-PERFORMANCE ALTERNATIVES TO PFAS

6th February 2025

Technical Manager
Nuno Sereno

CONTENTS

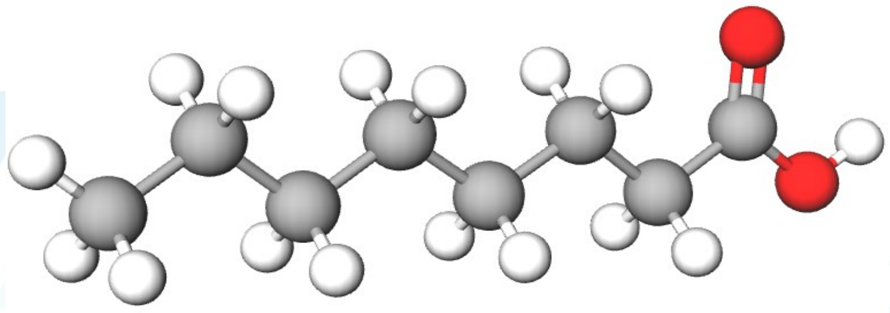
WHAT ARE PFAS?

- **PFAS** – An acronym for **P**er *and Poly* **F**luoro**A**lkyl **S**ubstances.
- Defined by the Organisation for Economic and Co-operation and Development (OECD)

PFAS are any chemicals with:

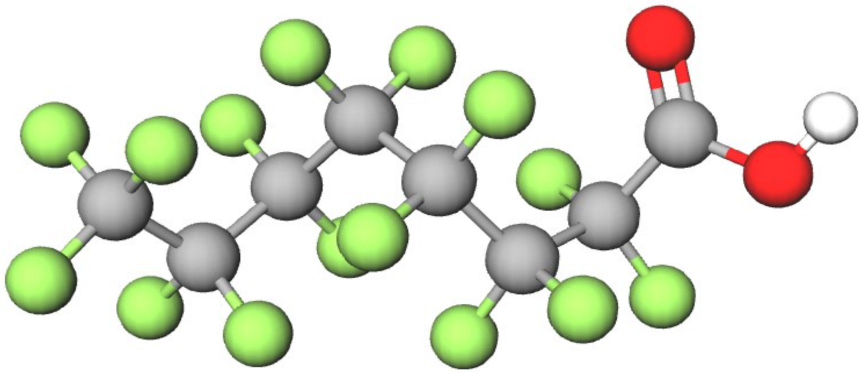
- **at least one perfluorinated methyl group (-CF3)** *or*
- **at least one perfluorinated methylene group (-CF2-)**

As a *Non* PFAS example – octanoic acid is an organic acid containing 8 carbon atoms, terminated with an acid group. In the picture below, C atoms are grey, H are white and O are red



Taking octanoic acid, If we replace ALL the hydrogens in the alkyl group with fluorine atoms, we get perfluoro-octanoic acid (**PFOA**), which is a PFAS.

In the picture below, fluorine (F) atoms are green, C atoms are grey, H are white and O are red.



INTRODUCTION TO PAEK POLYMERS

(Poly-)Aryletherketones:

- Thermoplastics
- Semi-crystalline
- Linear, Aromatic

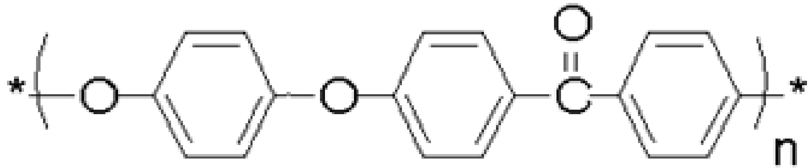
Groups

- Aryl: benzene ring
- Ether: R-O-R

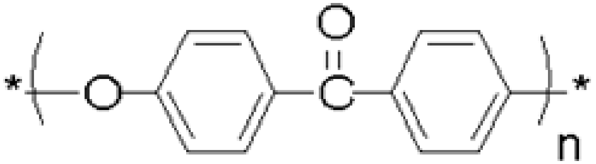
O
||
- Ketone: R-C-R

Major Types:

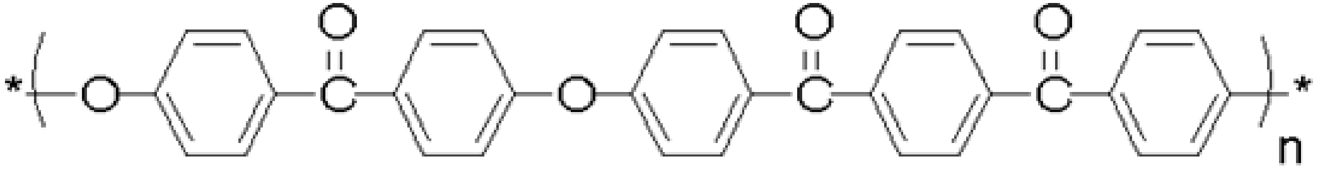
▶ PEEK



▶ PEK (Victrex HT™)

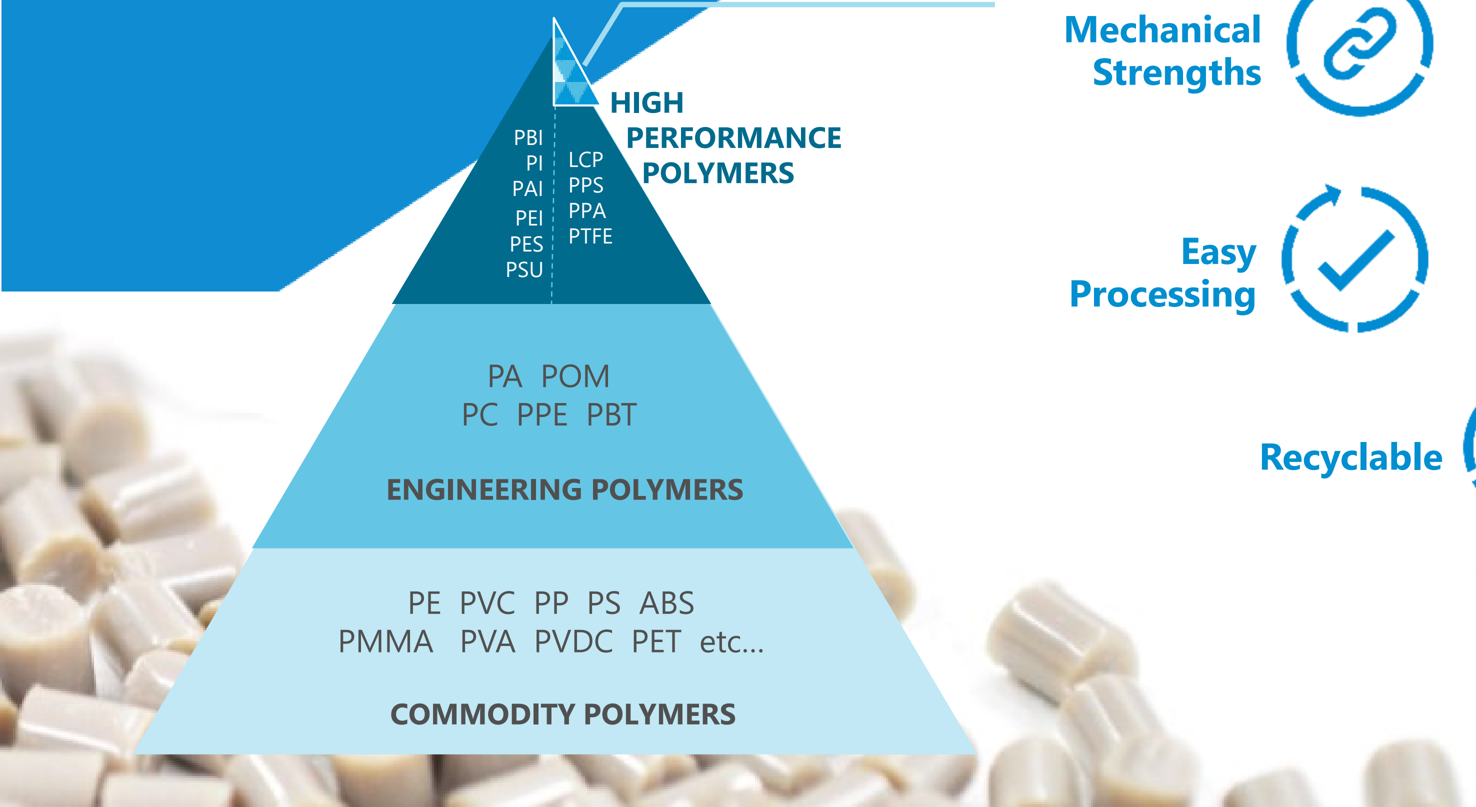


▶ PEKEKK (Victrex ST™)



VICTREX™ PEEK & PAEK POLYMERS

A Versatile Solution



victrex

VICTREX PEEK & PAEK PRODUCTS

VICTREX PEEK & PAEK Polymer Options for PFAS Replacement

PEEK Polymers

One of the world's highest performing polymers

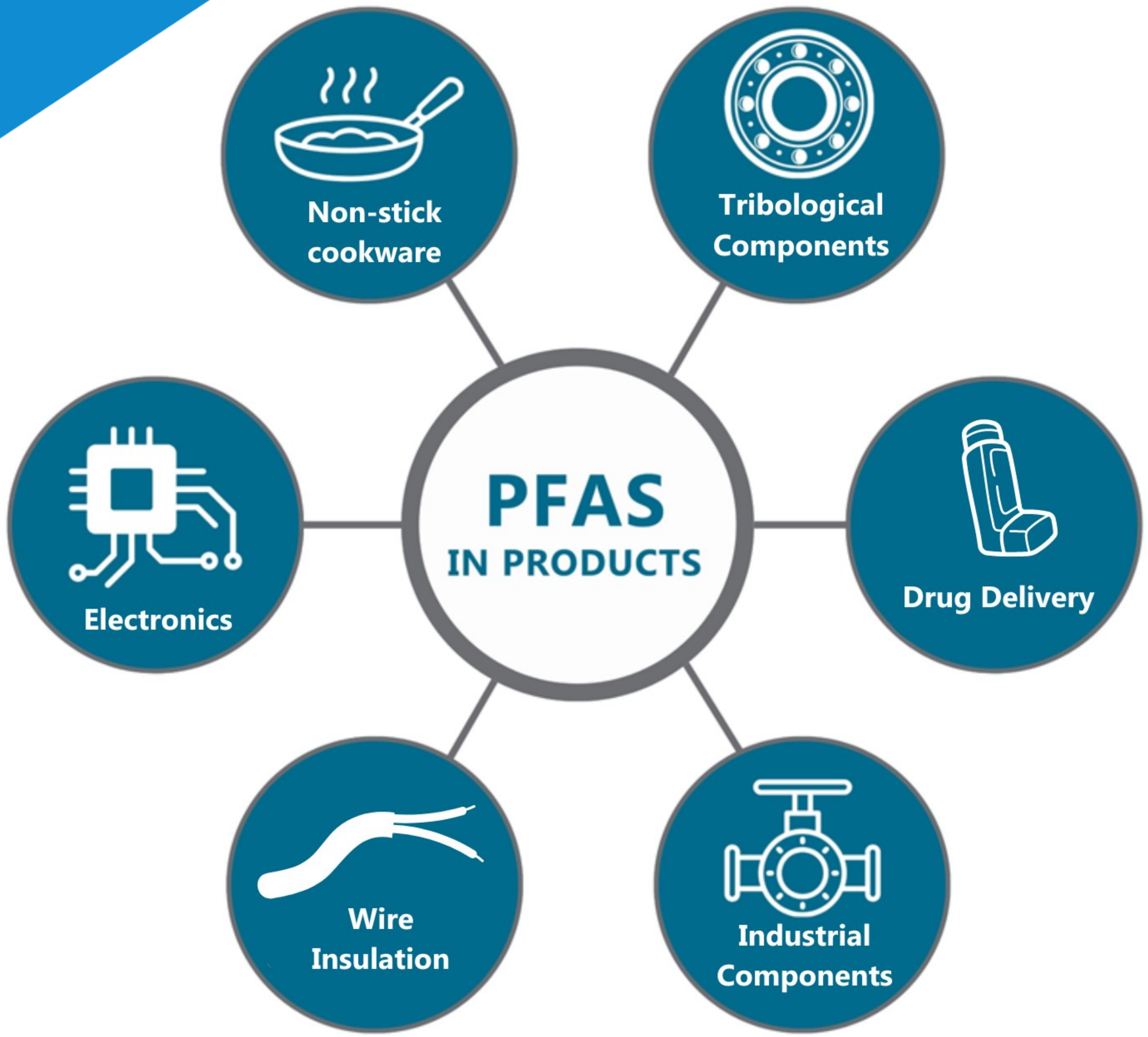
- 450G™ - all-purpose grade
- VICTREX WG™ - Higher wear performance
- VICTREX FG™ - For food & Beverage
- VICTREX PC™ - Non-implantable Medical grade
- VICTREX CT™ 100 – for Cryogenic applications

LMPAEK™ Polymers

PAEK polymer lower melt properties, increased manufacturing possibilities

- VICTREX LMPAEK™
- VICTREX AM™
- VICTREX AE™
- VICTREX LMPAEK™ Compounds (in development)

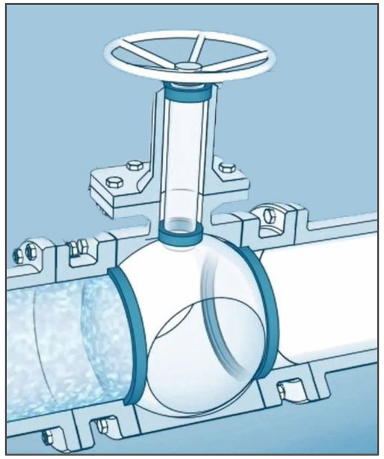
APPLICATIONS FOR PEEK AS A PFAS REPLACEMENT



PAEK & PEEK APPLICATION EXAMPLES

victrex

Valves & Seals Pipe, Tubing



- Sealing capacity
- Low friction (valves)
- Chemical Resistance

Bearings

- Low friction
- Long wear life

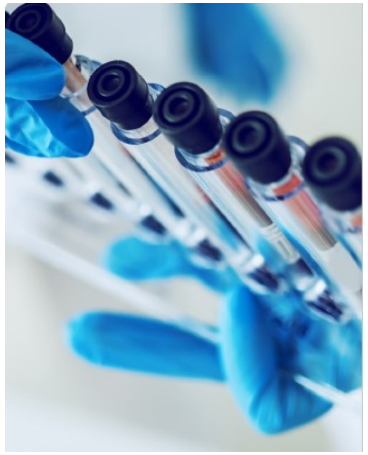
Wire Coating

- High dielectric strength
- Low loss

Food & Water Contact

- Mechanical performance
- Food regulatory compliance
- Chemical resistance

Pharmaceutical Contact



- Sealing
- Purity, biocompatibility
- Chemical resistance

VICTREX PFAS-ALTERNATIVES BY APPLICATION

Application	Function	Incumbent Fluoropolymer	Victrex Product
Seals and Valves	• Sealing • Anti-extrusion performance < 100 bar (PTFE) > 100 bar (PEEK)	PTFE Moly-Filled PTFE Glass-Moly PTFE Polyimide-Filled PTFE	VICTREX PEEK, VICTREX HT™ VICTREX ST™ Reinforced & Lubricated grades APTIV™ PEEK Film LMPAEK™ polymers
Cryogenic Seals and Valves	• Sealing • Ductility LNG: -161.5°C LH_2: -253°C	PTFE PCTFE PTFE	VICTREX CT™ 100 (maximum ductility)
Bearings	• Low COF • Low Wear Rates	PTFE-based formulations	VICTREX WG™ 101 (high pressure • velocity, PV) VICTREX WG™ 102 (high PV and high T service)
Wire Coating	• Insulation (dielectric strength) • Low dielectric loss • Chemical resistance • High temperature resistance	PFA, PVDF, FEP	PEEK VICOTE™ 700 (powder coating)
Food and water contact	• Food regulatory compliance* • Chemical resistance • Mechanical strength • Low friction & wear	PTFE	VICTREX FG™ polymers
Pharmaceutical contact - primary packaging stoppers	• Sealing, purity, biocompatibility, chemical resistance	PTFE	VICTREX PC™ grades APTIV™ PC film

VICTREX PFAS-ALTERNATIVES BY PROPERTY

Key: '✓' indicates an attribute of the material

		Fluoropolymers			Victrex PEEK & PAEK PFAS Alternative Options					
		PTFE	PCTFE	PVDF	Victrex PEEK	Victrex CT	Victrex WG Wear Grades	VICTREX FG Food Contact	Victrex PC Pharma grade	LMPAEK
Mechanical	High ductility	✓			✓	✓	✓	✓	✓	✓
	Low temperature ductility		✓			✓				
	High temperature resistance				✓	✓	✓	✓	✓	✓
	Sealing (compliance)	✓	✓	✓	✓	✓		✓	✓	✓
Thermal Properties	Lower melting temperature									✓
Chemical	Inert to many chemicals	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Low Water Absorption	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Low Flammability	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Thermal Stability	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Purity and Biocompatibility	✓							✓	
Tribology	Low COF	✓			✓		✓	✓		
	Low wear rates	✓			✓		✓	✓		
Electrical	High dielectric strength	✓		✓	✓			✓		
	Low loss	✓		✓	✓			✓		

MECHANICAL PROPERTIES COMPARISON

Properties	450G™ PEEK	Victrex PC	APTIV film	LMPAEK	PVDF	PTFE+25%GF	PTFE (neat)
Young's Modulus (GPa)	4	4	1.8-4.8	2.9	2.3-1.2	~1.3	0.6
Tensile Strength (MPa)	98	98	100-120	90	55-45	14.5	26.9
Strain at Break (%)	45	45	> 100	60	20-100	270	300
Coefficient of Friction (COF)	0.35	0.35	n/a	0.35 (est.)	0.14	0.07-0.12	0.05

- **LMPAEK Solutions as Alternatives to PFAS:**
  - *LMPAEK (neat):* replacement for stiffer fluoropolymers (i.e. PVDF).
  - *LMPAEK Compounds:* modification to achieve novel properties

VICTREX LMPAEK™ PRODUCT OPTIONS

Product	Description	Flow
LMPAEK™ Polymer 101 GRA	Low viscosity Granule	Easy flow
LMPAEK™ Polymer 101 PWD	Low Viscosity Course Powder	
LMPAEK™ Polymer 101 FPD25	Low Viscosity, Fine Powder	
LMPAEK™ Polymer 103 Granule	Medium Viscosity Granule	Standard flow
LMPAEK™ Polymer 231 Granules	Low Viscosity, 30% Carbon Fibre	Low flow

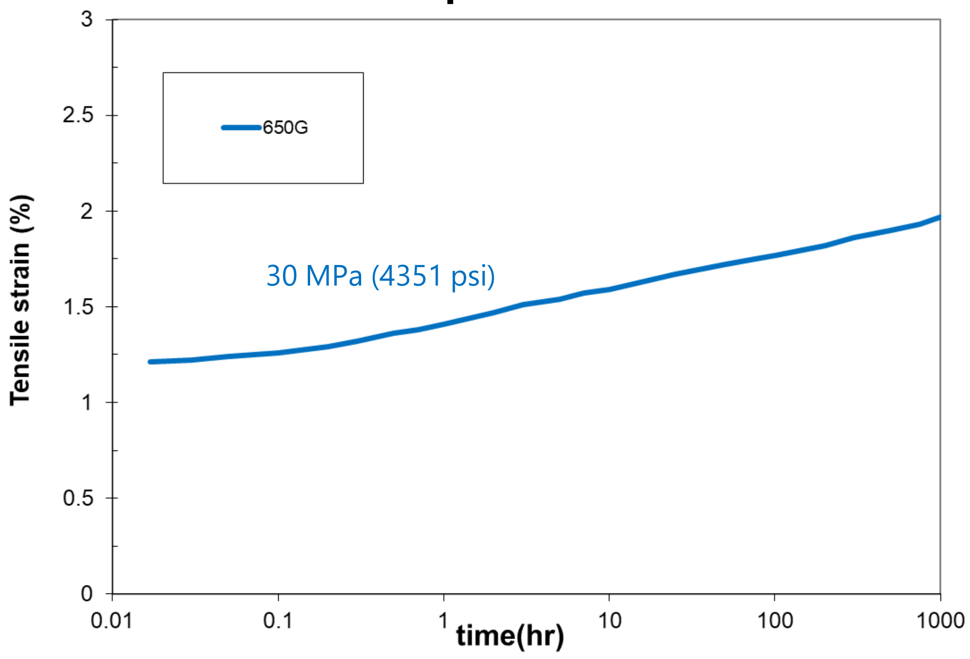
- **Products:**
  - LMPAEK™ polymers are the latest members of the PAEK family, developed by Victrex
- **Options:**
  - *LMPAEK:* replacement for stiffer fluoropolymers (i.e. PVDF).
  - *LMPAEK* compounds: modification to achieve novel properties

TENSILE CREEP PERFORMANCE AT ELEVATED TEMPERATURES

Application examples: Seals, Bearings, Wire Coatings, Food & Water Contact, Pharmaceutical etc.

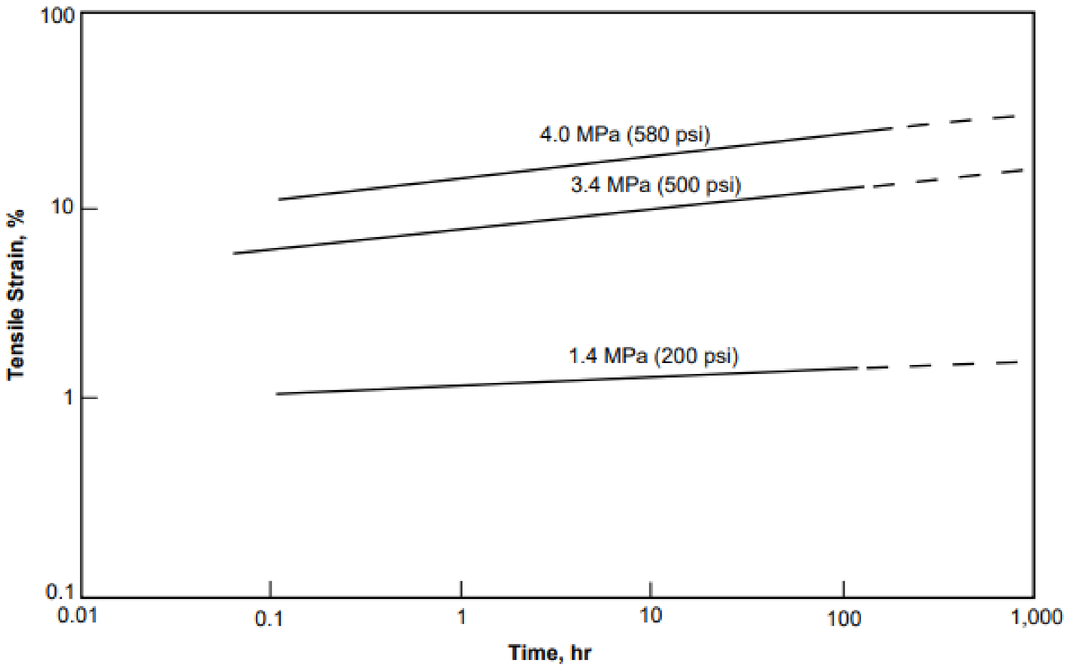
VICTREX PEEK undergoes much less creep compared to PTFE despite higher temperatures and stresses.

Tensile Creep of PEEKs at 120°C



Reference: Victrex internal study

Tensile Creep of PTFE at 100°C



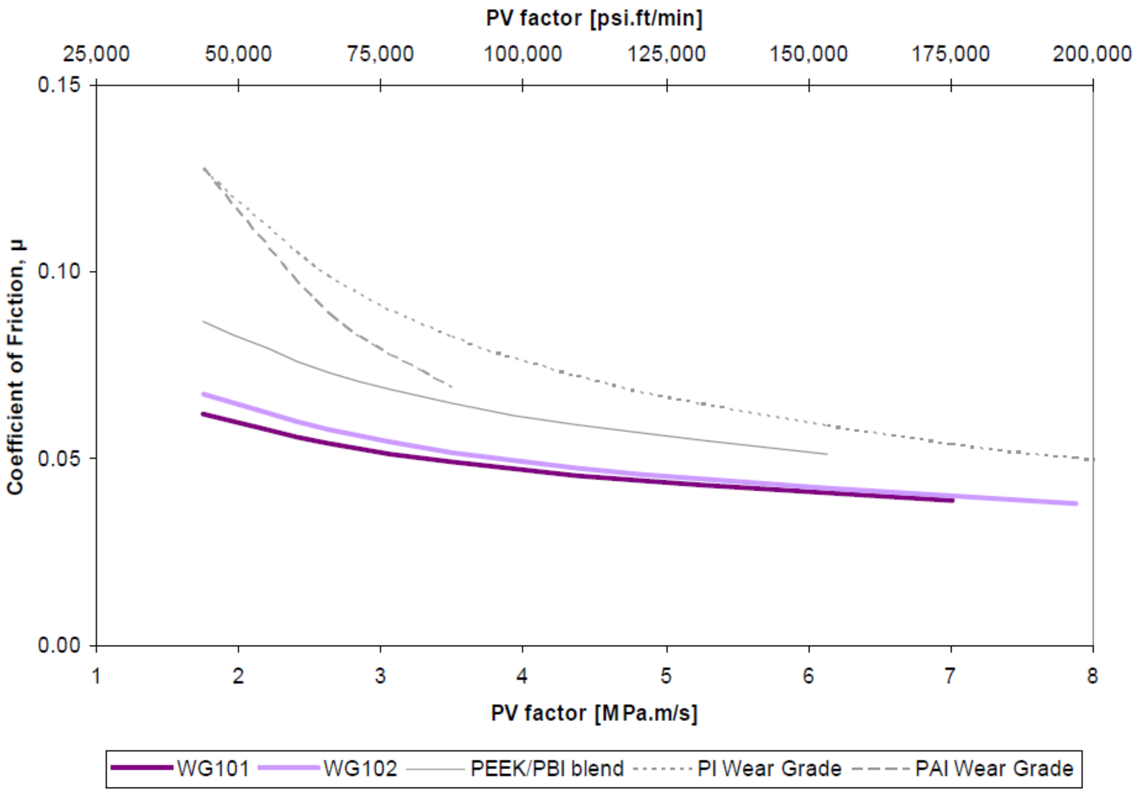
Reference: DuPont™ Teflon® PTFE Fluoropolymer Resin Properties Handbook

Creep resistance may translate to advantaged dimensional stability in sealing applications

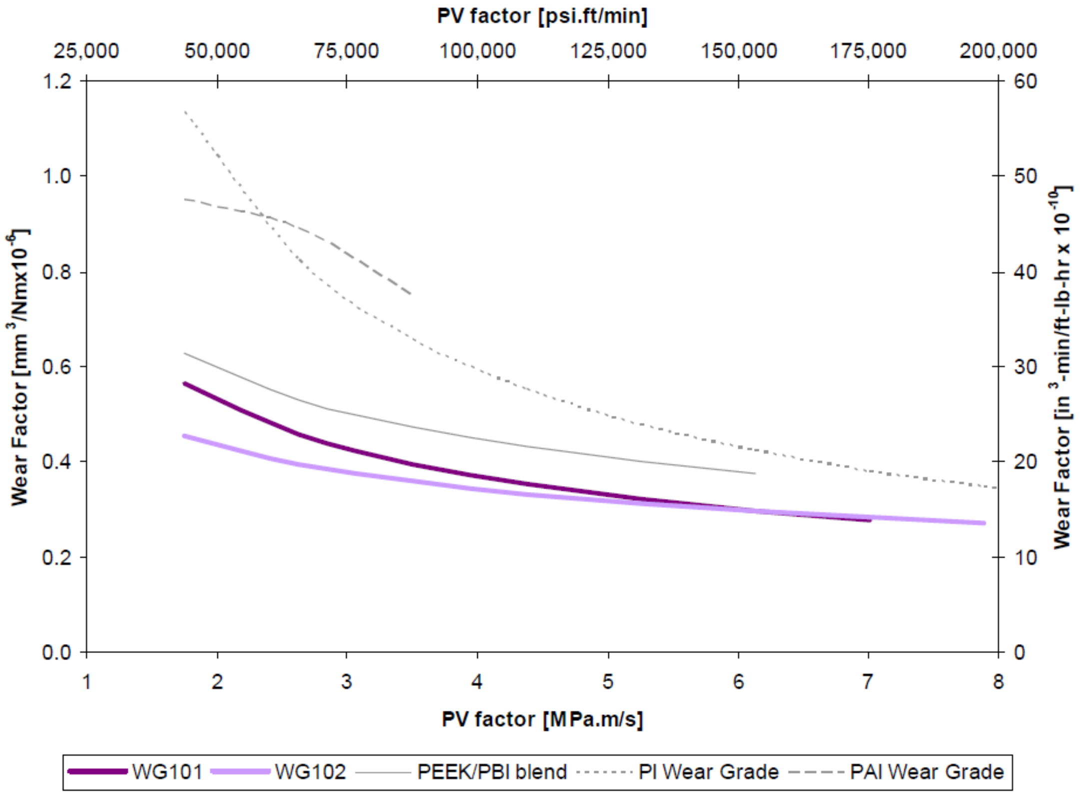
TRIBOLOGICAL PROPERTIES

Examples: Bearings and other dynamic sealing applications

Coefficient of Friction (ASTM D3702)



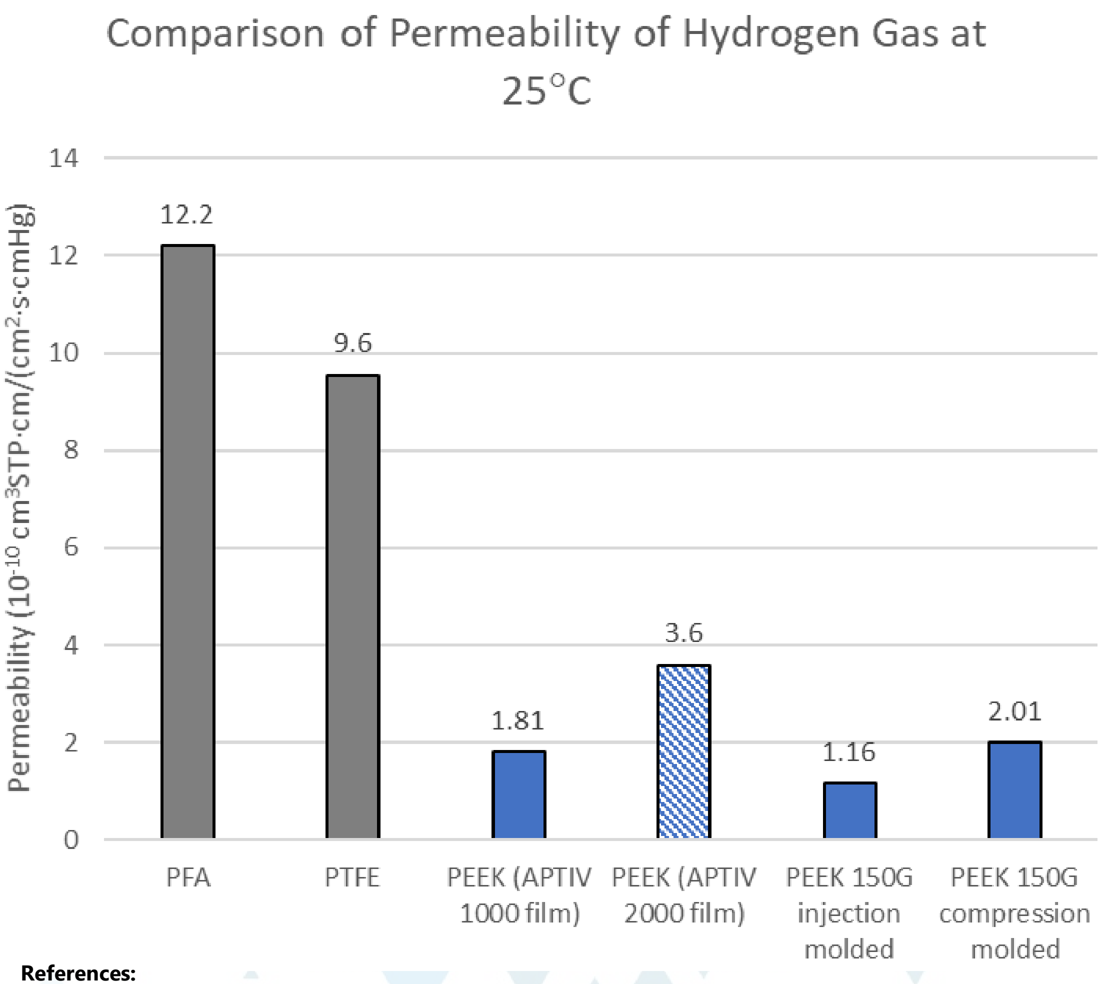
Wear Factor (ASTM D3702)



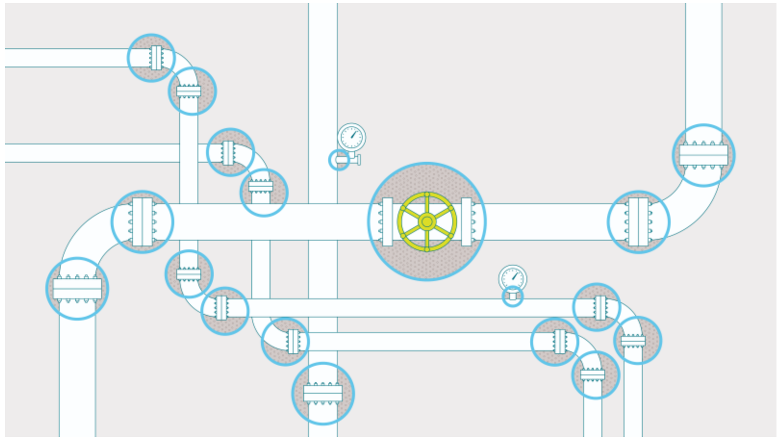
VICTREX WG™ PFAS-free bearing grades exhibit low friction and low wear rates

PERMEABILITY TO H_2

Application examples: Sealing, Pipe, and Tubing



- **Applications:** Seals (dynamic and static)



- **Observations:** Victrex PEEK at 63-90% to lower permeability to hydrogen gas compared to PFA and PTFE.
- **Conclusion**: Lower permeability of PEEK can contribute to lower fugitive emissions.

References:

- *Gas Permeation Resistance of Fluoropolymers* (Entegris Inc.)
- Menon et. al., *Proc of the ASME 2016 Pressure Vessels and Piping Conf* PVP2016-63713
- Yavari et.al. *J Membrane Sci* 548 (2018) 380-389.
- Monson et. al *J App Polym Sci* 127 (3) 1637-1642.

SUMMARY

- **Victrex PEEK and PAEK polymers are a sustainable, high-performance alternative to PFAS:**
  - Mechanical properties
  - Chemical resistance
  - Purity / Biocompatibility
  - Tribology (low friction and wear)
  - Electrical (high dielectric strength, low loss)
- **Available forms:**
  - Pellets (granules), powder
  - Film
  - Powder and liquid dispersions for coatings
- **Suitable processing methods:**
  - Melt processing (injection moulding, compression moulding, extrusion)
  - Coatings

VICTREX DIFFERENTIATION:

A PARTNER – FOR TODAY AND THE FUTURE

- Accelerate the creation of new markets, by anticipating and investing to meet market need
- Proven track record in pioneering PAEK-based innovation
- Delivering unparalleled technical expertise, and in-depth application and market knowledge
- Enabling technologies that improve performance in extreme environments
- Security of supply

MORE INFORMATION

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Advanced siloxane coatings as alternatives to fluoropolymers

Alan Taylor

Overview

Objectives

- To highlight existing non-PFAS technologies from mature supply chains that could provide alternative products for coating applications

Content

- Context
- Key characteristics and performance metrics
- Underpinning chemistries
- Exemplars
- What next?

Why are PFAS useful and where are they used?

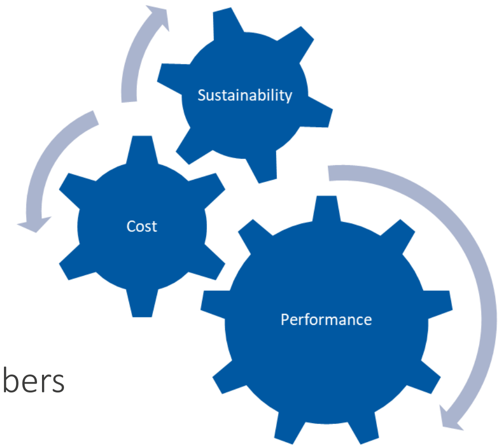
- Resistance to corrosion and chemical attack
- -200 to +260°C for PTFE and PFA
- Low coefficient of friction
- Low and ultra low permeation rates
- UV resistance, optical transparency
- Electrically insulating
- Good fire safety
- Mature technology
- Established supply chains
- Qualified products
- ~$30Bn industry sector

Industry sector	Non-polymer products	Polymer products
Aerospace	Additives in hydraulic fluids	Insulators, seals
Construction	Additives in coatings and paints	Coatings
Automotive		Low friction bearings and seals, lubricants
Electronics	Flame retardants	Insulators
Fire fighting	Additives to foams	Protective clothing, coatings for fire fighting equipment, fuel repellents
Oil and mining	Additives for oil well stimulation Polymer processing aids (PPAs)	Liners, seals
Consumer products		Non-stick coatings, textile treatments

FPG perspectives accompanying the Regulatory Management Option Analysis (RMOA) for fluoropolymers (FPs)
https://www.bing.com/search?q=FPG+perspectives+accompanying+the+Regulatory+Management+Option+Analysis+%28RMOA%29+for+fluoropolymers+%28FPs%29&form=ANNH01&refig=62a5e1443991459487952c5f65efa954&pc=U531

What are the direct and indirect business risks?

- Increasing complexity of regulation and regulatory uncertainty led
  - Potential restriction of all PFAS in EU27/EEA
  - EPA PFAS action plan (focus on TSCA and MCL)
- Product availability
  - Supply chain disruption/evolution[i]
- Future liabilities leading to potential insurance increases
  - $120-$175Bn for 140,000 water districts in the US [ii]
  - Litigation further up the supply chain is being seen in increasing numbers
- Increasing product compliance costs
- Product end-of-life management
- Increasing costs
  - EPA will use "every enforcement tool" in its PFAS regulation efforts [iii]
- Environmentally directed finance standards
  - Investor Initiative on Hazardous Chemicals with portfolio worth $60Tn [iv]



i - https://news.3m.com/2022-12-20-3M-to-Exit-PFAS-Manufacturing-by-the-End-of-2025
ii- https://www.milliman.com/en/insight/pfas-liability-estimate-water-district-remediation
iii -https://www.dechert.com/knowledge/onpoint/2023/10/pfas---the-rising-tide-of-regulatory-compliance-and-litigation-r.html
iv -https://chemsec.org/knowledge/iihc/

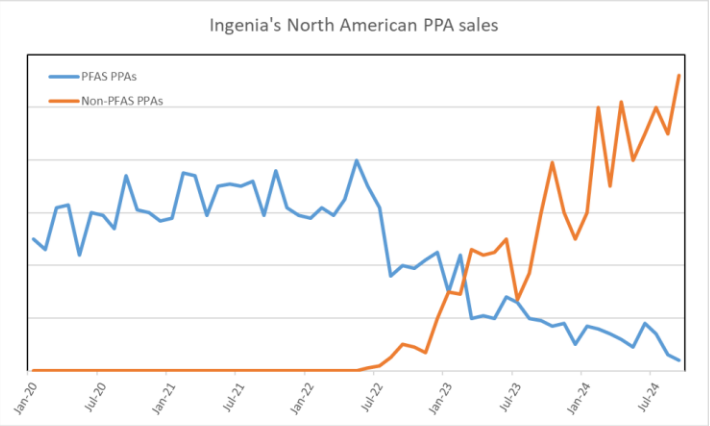
Emerging opportunities?

- New ecosystems are emerging, covering:
  - PFAS consulting services
    - Supporting companies navigate regulations in the products, sectors and geographies of interest. Developing management plans, risk assessments and compliance support
  - PFAS testing and analysis
    - Product and supplied material evaluation to ensure compliance with specifications and regulations
  - PFAS-free product development
    - New materials, formulations, manufacturing processes.
  - PFAS remediation services
    - Waste stream and water management services. End-of-life product recycling and disposal/destruction
  - PFAS expert litigation lawyers

Non-PFAS and PFAS-free alternatives

- Alternatives are being explored for areas such as:
  - Hydrogen economy
  - Sustainable food packaging
  - Low materials for 5G
  - Thermal management for data centres
  - Electric vehicles
- PFAS free FR polycarbonate and PC/ABS
- PFAS free PPA replacements
- Membrane materials
- Electrolysers for hydrogen production
- A wide range of products are being placed on the market

https://www.trinseo.com/Solutions/PC-ABS/EMERGE
AMI PFAS Worshop September 2024
https://www.ionysis.com/
https://ionomr.com/



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Chemical basis of fluoropolymers

- Strong, stable bonds between the fluorine and carbon leading to chemical and thermal resilience
- Low free energy values of perfluorinated groups leads to low free energy and hydro/oleo philicity

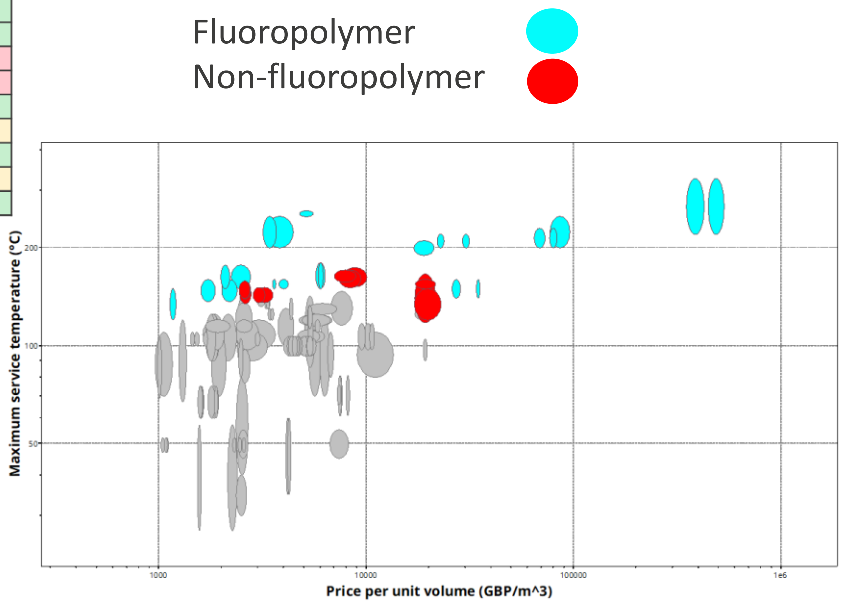
Bond type	Bond energy (kJ/mol)
C–F	439
H–C	415
O–Si	370
C–Si	360
C–O	350
C–C	345
C–N	290

Chemical group	Free energy (mN/m)
$-CF_3$	15
$-CF_2$	23
$-CH_3$	30
$-CH_2$	36

Thermal and chemical resilience of polymers

	Polymer				
	PTFE	PVDF	PPS	PEEK	PEI
Working temperature (°C)	260	150	240	250	170
Temporary temperature (°C)	290	150	270	310	210
Chemical class					
Dilute acids	1	1	1	1	1
Concentrated acids	1	1	1	2	1
Diluted base	1	1	1	1	1
Concentrated base	1	3	4	1	5
Aromatic hydrocarbons	1	4	1	1	5
Aliphatic hydrocarbons	1	4	1	1	1
Esters and ketones	1	1	1	1	4
Ethers	1	1	1	1	1
Chlorine based solvents	1	1	3	1	4
Alcohols	1	1	1	1	1

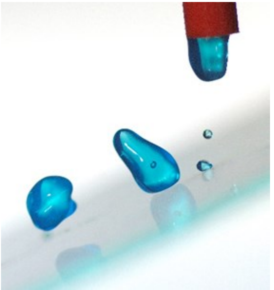
Table adapted from: Zywica, G etal; 1028. "Design and Manufacturing of Micro-Turbomachinery Components with Application of Heat Resistant Plastics". Mechanics and Mechanical Engineering 22 (2) 649-660



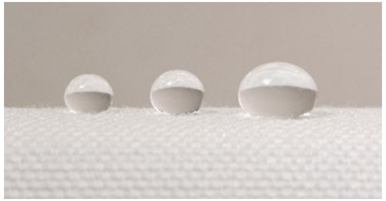
- Materials selection options may be wider than expected
- Revision of operation specification may highlight existing non-PFAS alternatives
- Qualification would still be required

Polysiloxane coatings overview

- Polysiloxanes are routinely added to organic resins
- There are a multitude of variants
  - Molecular weight/size
  - Chemical structure (linear or branched)
  - Functionality
  - Content (5 – 90%)
- Advantages
  - Improved heat stability
    - Up to 200°C for methyl siloxanes and 250°C for phenyl siloxanes
  - Improved weathering resistance
  - Improved water repellence
  - Enhanced release and easy clean properties
  - Reduced viscosity (VOC benefits)



we have ignition" by ndrwfgg is licensed under CC BY 2.0



Truck exhaust stack" by Matthew Paul Argall is licensed under CC BY 2.0

Silicon based alternatives (silane, silicone, siloxane, polysiloxane, polysilazane, silsesquioxane ………)

Silicone elastomers

Chemical basis	Name	Characteristics
Methyl silicone	MQ	Excellent ozone and UV resistance.
Phenyl methyl silicone	PMQ	Improved low and high temperature capabilities
Vinyl methyl silicone	VMQ	Improved temperature range and compression properties compared with MQ
Fluorovinyl methyl silicone	FVMQ	Improved chemical resilience, reduced hot air resistance

Name	Basic structure
M	CH_3 H_3C Si O CH_3
D	CH_3 O Si O CH_3
T	CH_3 O Si O O
Q	O O Si O O

Siloxane based coatings / surface treatments

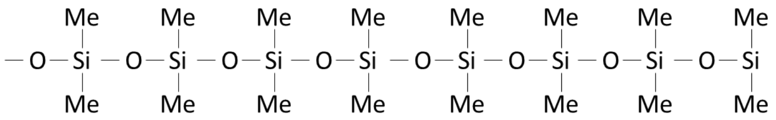
Chemical basis	Example	Nature
M	HDMZ	Hydrophobising agents
D	$Cl_2Si(CH_3)_2$	Surface treatments
T	Epoxy silane	Silane coupling agents, Cr(VI) replacement technologies
Q	TEOS	Binder for corrosion protective coatings
DT		PSA release coating
DTQ		Hydrophobic, anti-graffiti, scratch resistant coating
PDTQ		High temperature (>500°) corrosion protective enamel

TWI

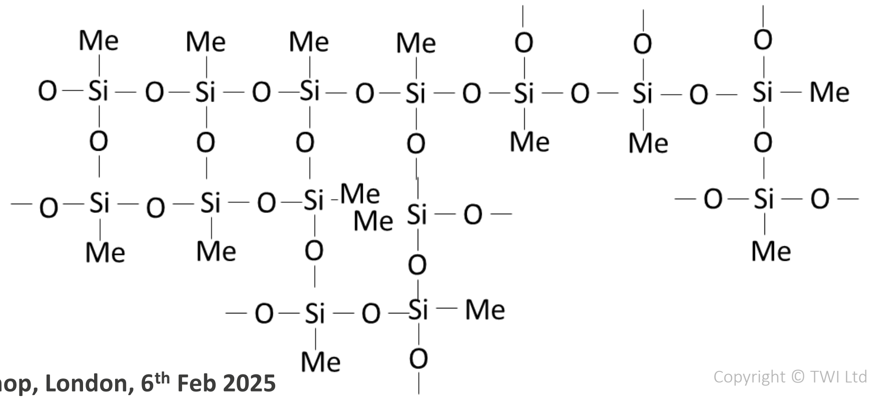
Siloxane based coating technologies

- Mature technology
- Vast range of products
- Inorganic/organic basis (polymer/ceramic)
- REACH compliant

Silicones are low viscosity, flexible, oxygen and moisture permeable inorganic polymers



Polysiloxanes are 3-D inorganic/organic polymer networks that cure to hard, thermally and chemically stable materials



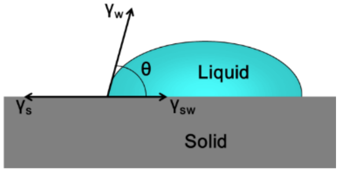
Ways to reduce adhesion

- Reduce chemical compatibility
- Reduce interfacial contact area
- Eliminate/reduce diffusion
- Combined mechanism – mechanical and chemical
- Maintain topographic and chemical characteristics

$$Abhesion = \frac{1}{Adhesion}$$

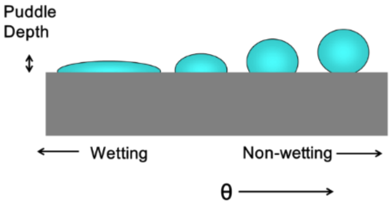
Surface wetting: A measure of repellence

- Surface energy estimation

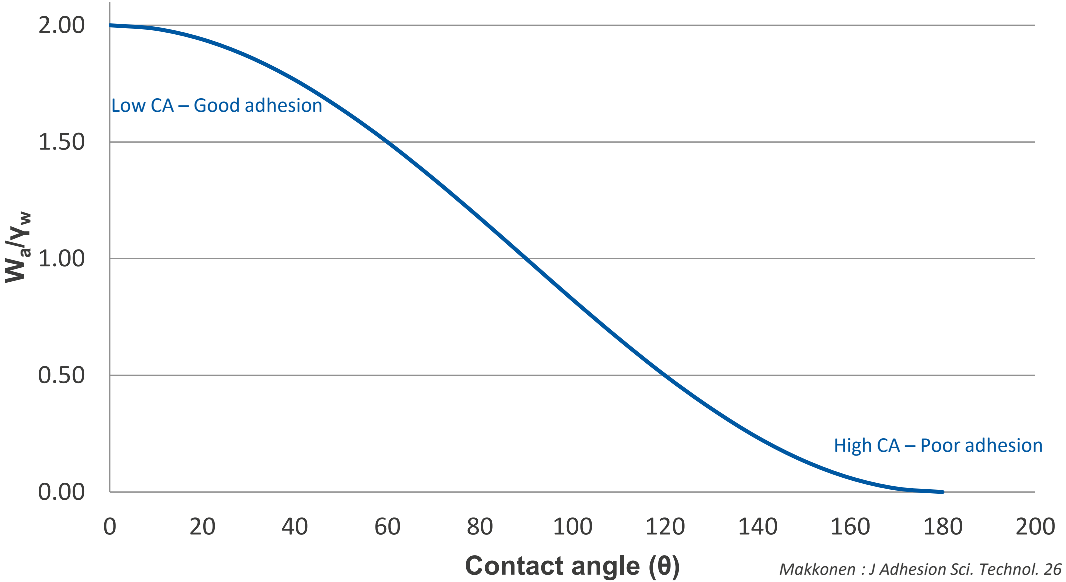


$\gamma_s = \gamma_w \cdot \cos\theta + \gamma_{sw}$ ***Young Equation***

Liquid-solid interactions
- Polar
- Dispersive
- Hydrogen bonding



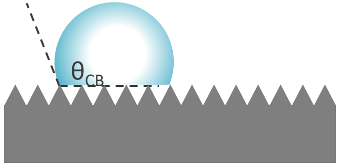
$$W_a \approx \gamma_w(1 + \cos\theta)$$



Makkonen : J Adhesion Sci. Technol. 26 (2012) 413-445

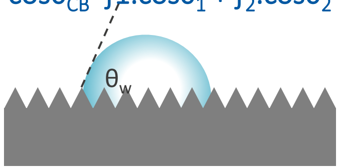
As the wettability decreases, surface contamination is easier to remove

Influence of roughness: Amplification of wetting behaviour



Cassie Baxter

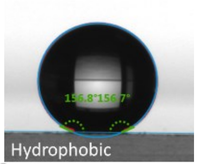
$\cos\theta_{CB} = f1.\cos\theta_1 + f_2.\cos\theta_2$

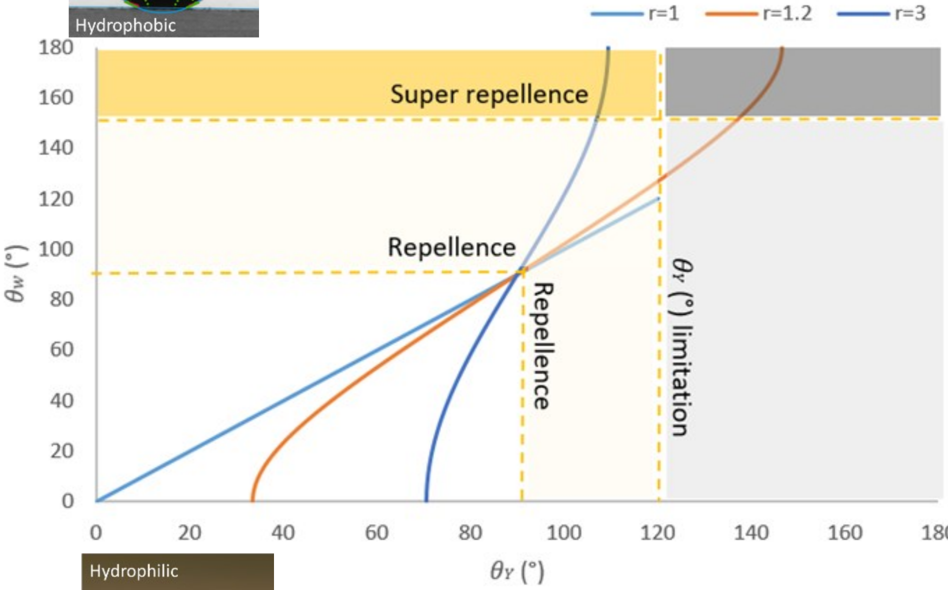


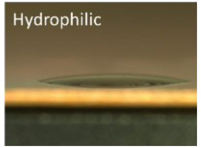
Wenzel

$\cos\theta w = r.\cos\theta$

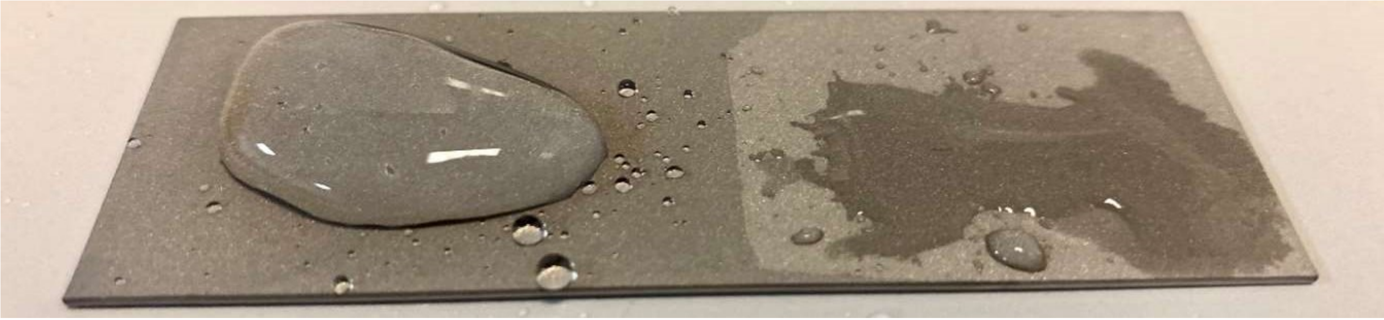
$$R_a = \frac{1}{L}\int_0^L |Z(x)|\, dx \qquad R_q = \sqrt{\frac{1}{L}\int_0^L |Z^2(x)|\, dx}$$







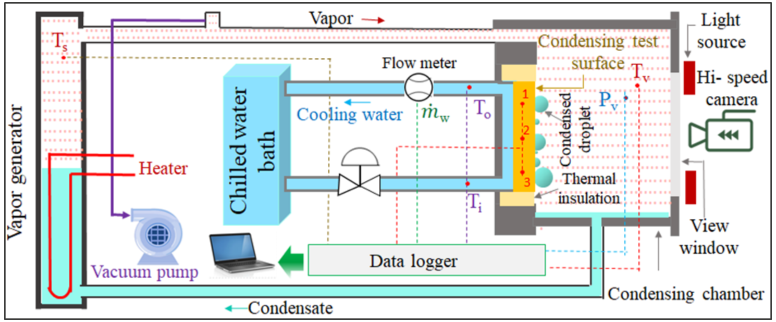
Switching from wettability to repellence

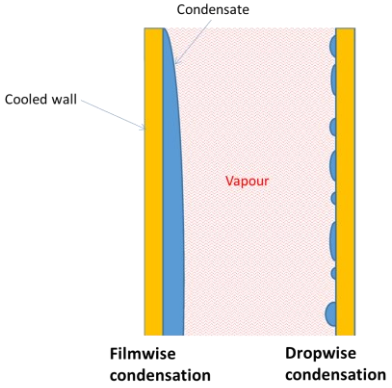


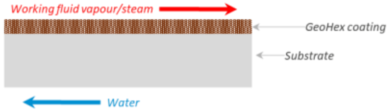
- Grit blasted 304 stainless steel
- The left hand side has been treated with a ~1µm thick film of a siloxane coating
- No significant difference the roughness of the two sides is measurable
- A simple example of the amplification of the intrinsic behaviour the surface

Increasing repellence

Case study – Repellent surfaces for condensers



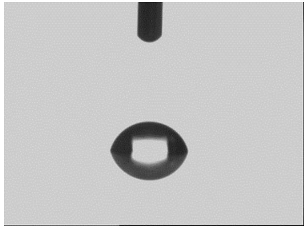




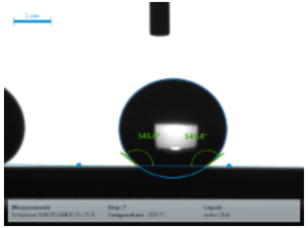
H2020 project GeoHex

- The aim was to promote dropwise condensation in the condenser of a heat exchanger to increase thermal efficiency
- A combination of roughness engineering and advanced high temperature polysiloxane (TQ) coatings enabled a superhydrophobic surface to be developed. The water contact angle increased from 75° to 150°
- Superhydrophobic treatments in condensers are expected to deliver 1-2% increases in efficiency.

Uncoated



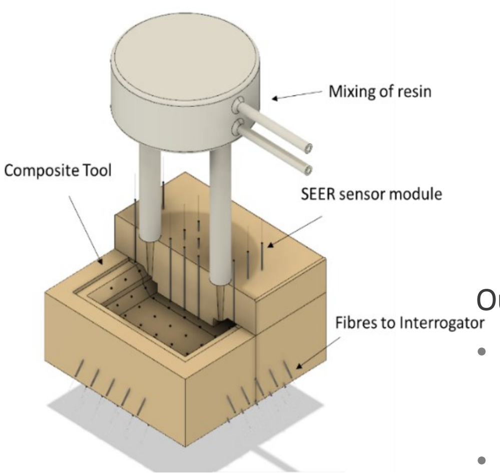
GeoHex coating



Water droplet on surface

Case study: Permanent, easy release transparent coating for sensors

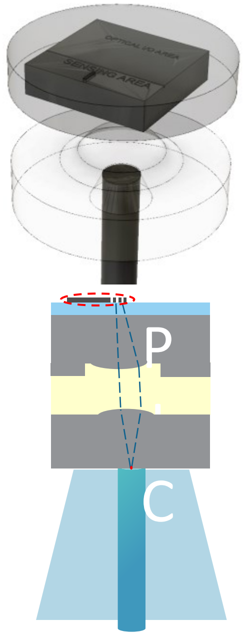
Resin injection in composite tool



To identify, select and optimise provide a coating for sensors used in composite part manufacture. The requirements are:

- Highly transparent
- Excellent adhesion to Si wafer
- Thermally stable
- Durable
- Cost-effective
- Permanent easy release to epoxy resins.

Illustration without housing



Outcome

- Optimised coating demonstrated allowing easy release of composite resin from the sensor.
- Demonstrated no interference with operation of the sensor enabling composite cure to be monitored.

Next steps

- Coated sensors will be embedded in tool mould and the real-time resin cure monitoring will be performed

TWI

Case study: Ice-repellent coatings for aircraft leading edge - IUK Project ICELIP

Problem

- Ice protection systems are complex, heavy and demand power. Minimising the formation of ice and its adhesion is viewed as highly desirable for next generation aircraft

Approach

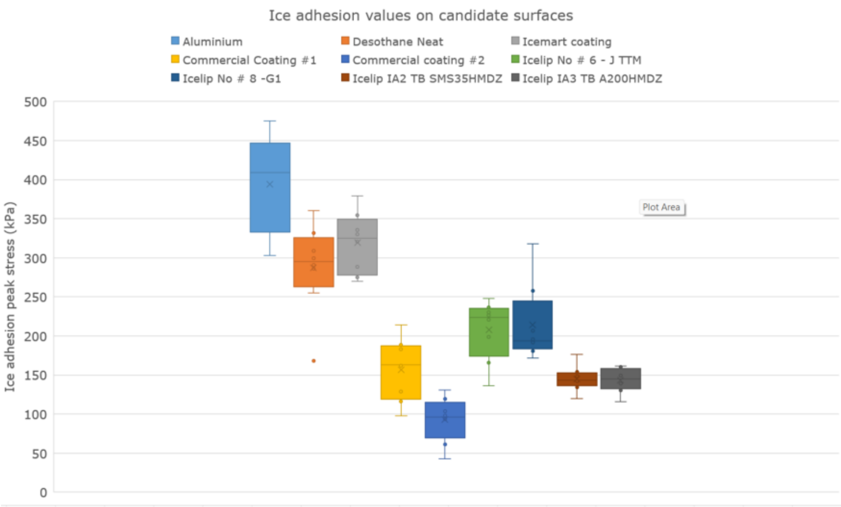
- Identification of siloxane (T) based coating resin
- Development of application and curing methodology
- Selection and incorporation of functional additives to de-icing power needs/weight and eliminate the use of harmful deicing fluids

Outcome

- The siloxane based coating was successfully modified The results from ice wind tunnel testing have shown that ice accretion is reduced upon the coating modification, also reduced the adhesion of ice to the surface

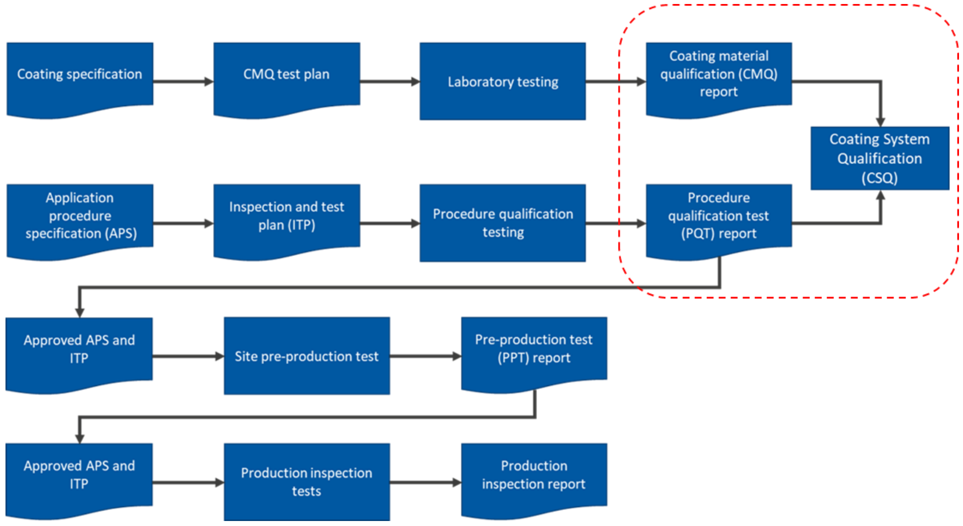
Benefits

- Reduction in power requirement for ice protection systems
- Supports transition to UK strategic FlyZero ambition



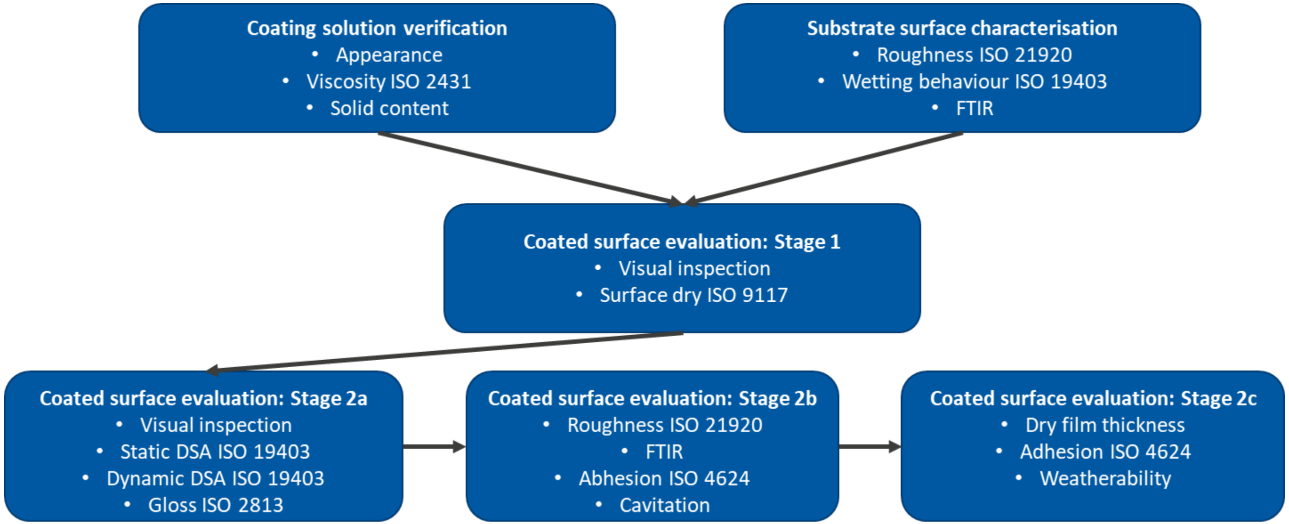
Identification, selection and qualification of siloxane coatings

- Qualification of a coating system is dependent on the properties of the selected coating material and its application methodology
- Coating selection is dependent on the specification and acceptance criteria
- Coatings are mainly solvent based but there are some water based products
- All are reactive systems and will cure under ambient conditions
- All benefit from heating to promote cure / full property development

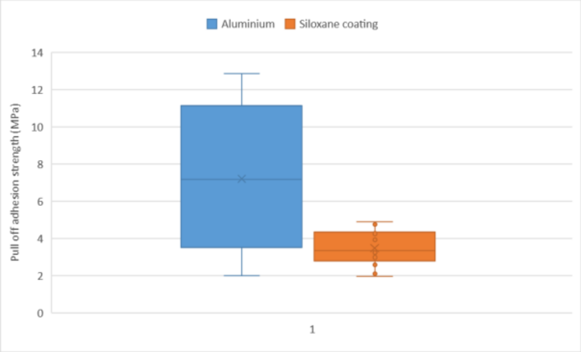


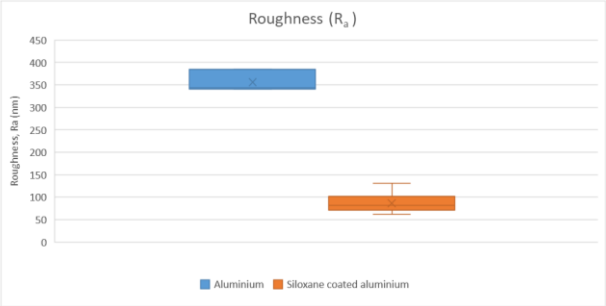
Coating specification development – coating for composites

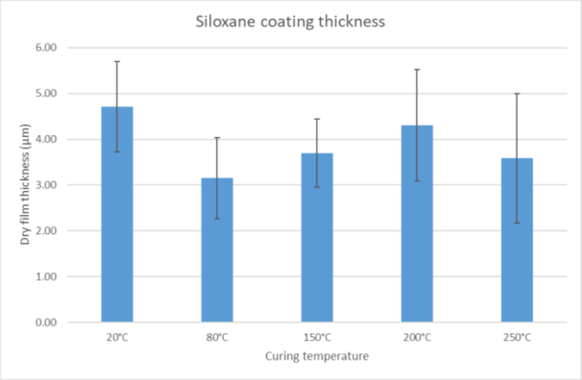
- Determine the desired key characteristics
  - Processing
  - Performance
- Identify test methodologies and standards
- Specify acceptance criteria
- Develop test plans (CMQ & ITP)
- Identify candidate coatings and evaluate (CSQ)

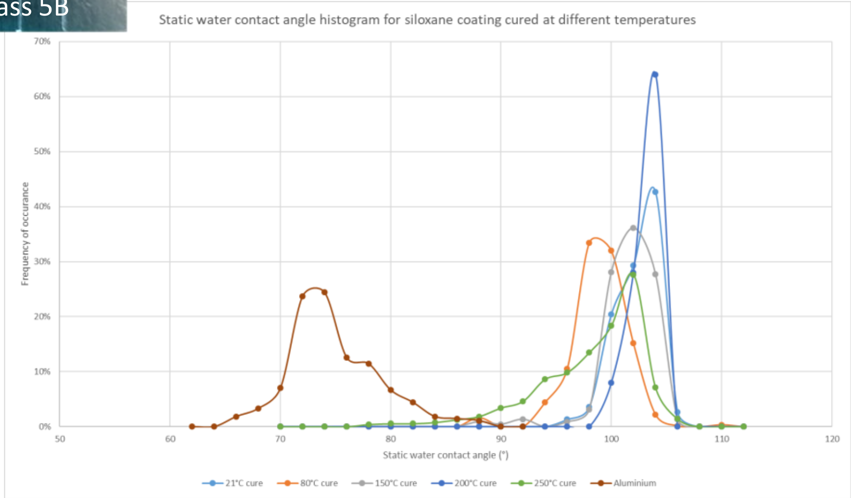


Siloxane coating evaluation – preparation for application on composite









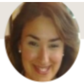
Summary and next steps

- The business risk surrounding PFAS is increasing
- Siloxane based materials are potential alternatives
- Mature supply chains exist and there is active product development particularly for coatings
- Increasing numbers of products are being made available
- TWI has considerable experience in the identification and comparative assessment of candidate coating technologies
- TWI launched a Joint Industry project to provide support to industry partners
- https://www.twi-global.com/media-and-events/press-releases/2025/pfas-managing-the-increasing-business-risk

Thank you

Alan Taylor FRSC FIMMM
Technology Fellow at TWI

Sara Naderizadeh, PhD
Senior Coating Engineer/ Project Leader at TWI



Sofia Sampethai, CEng
JIP Programme Manager at TWI

BioHalo

The Biohalogenation Company

PFAS contaminates environments all over the globe, and is found to exist in the blood of nearly all people on earth with huge potential health consequences.

PFAS – Forever Chemicals

>25 billion €
global annual market size

>20.000
known contaminated EU sites

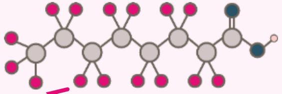
>50 billion €
annual health-related costs in the EEA

The world needs PFAS replacements!

Sources:
Market size – Statista: https://www.statista.com/statistics/1454431/global-pfas-market-value-by-application/
Contamination sites – Le Monde: https://www.lemonde.fr/en/les-decodeurs/article/2023/02/23/revealed-the-massive-contamination-of-europe-by-pfas-forever-chemicals_6016906_8.html
Health cost – Nordic Council of Ministers (website): https://www.norden.org/en/publication/cost-inaction-0
Health cost – Nordic Council of Ministers (pdf): http://norden.diva-portal.org/smash/get/diva2:1295959/FULLTEXT01.pdf

Fluorine drives our modern society

Per-and polyfluoroalkyl substances -PFAS



Fluorine

Fluorine content hard to adjust

Toxic

Non-recyclable

>10.000

Known & used PFAS

Impending ban of PFAS EU

Fluorine adds the **high-performance** to **advanced materials**

- Chemical resistance
- Heat tolerance
- Moisture repellency
- Electrical insulation

PFAS-using industries

Cosmetics · Food packaging · Construction · Industrial applications and equipment · Automobile · Outdoor clothing · Medical devices · Semi-conductors · Electronics · Defence · ...

Sources:
Biggeri et al. (2024): https://doi.org/10.1186/s12940-024-01074-2
Purdue at al. (2023): https://doi.org/10.1289/EHP12603
Sonne et al. (2023): https://doi.org/10.1016/S2542-5196(23)00106-7

BioHalo

A team capable of starting a revolution

Executive leadership

Nicolas Krink
Co-founder & CEO
- Expert in strategic growth and fundraising
- Strong venture capital network and experience
- Expertise in synbio and metabolic engineering

Mariela Mezzina
Co-founder, CSO & COO
- Leads scientific efforts and soft fundraising
- Over a decade in metabolic engineering
- Developed fluorinated biopolymers at DTU

R&D

Pablo Nikel
Co-founder
- Over 150 publications, h-index 51
- Multiple biotechnological patents and awards
- Editor-in-Chief, Current Opinion in Biotechnology

Alberto De Maria
Head of Science
- Oversees strain engineering and optimization
- Expertise in organofluorine biosynthesis pathways
- Skilled in biomanufacturing and fermentation

Justine Turlin
R&D Project Associate
- Experienced in R&D project management
- Expertise in patent application filing
- Skilled in grant proposals writing

Arthur Vancolen
Research Assistant
- Expert in protein expression and genetic engineering as well as in enzymatic processes
- Strong lab management foundation

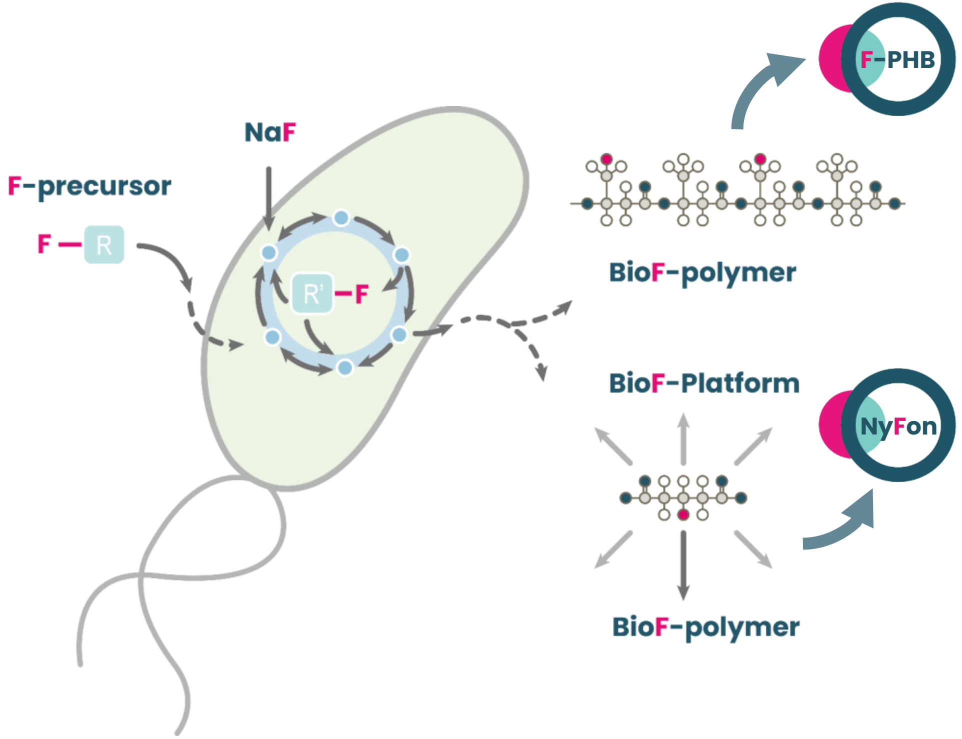
Business & operations

Johann Liebeton
BD Lead
- Business development and market growth
- Strong networker with cross-industry connections
- Proven ability to drive early-stage operations

We use a new-to-market technology based on microorganisms, which has significant benefits for the production

We use microorganisms to create two types of polymers, F-PHB and NyFon…

…in a process that allows us to control fluorination levels. This differentiates our product by having CF bindings, rather than CF_2 or CF_3.



Our patented biofluorination technology…

…reduces energy needs, can utilize renewable carbon feedstocks, minimize toxic emissions, and has fewer byproducts compared to traditional PFAS production.

Low energy needs
The fermentation step is performed at mild temperature (25-40ºC).

Renewable & waste as feedstock
The fermentation feedstock can be derived from various waste stream instead of petroleum derived chemicals or toxic starting materials.

60% reduced GHG emissions
Our flagship product F-PHB reduces GHG emissions by 60% compared to PTFE.

Low pollutant generation
Our technology does not release toxic pollutant during synthesis.

Minimal by-products
Our biofluorination technology is characterized by high specificity and low by-products formation.

Controlled mono fluorination
Our biofluorination technology introduces CF bonds at specific positions instead of unspecific CF_2 and CF_3.

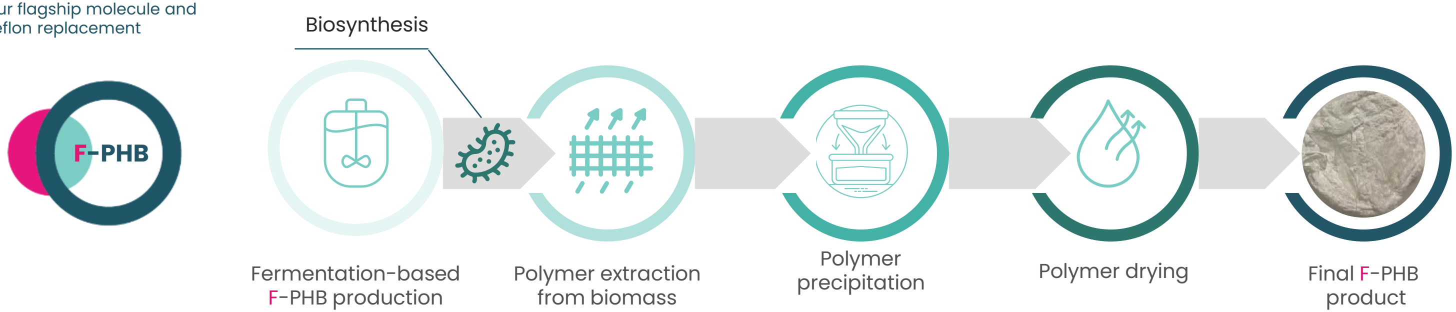
BioHalo

We have patented two unmatched new-to-market products

Our production process harness the potential of our microbial platforms to produce novel fluorinated polymer or fluorinated building block that chemistry synthesis deemed impossible.

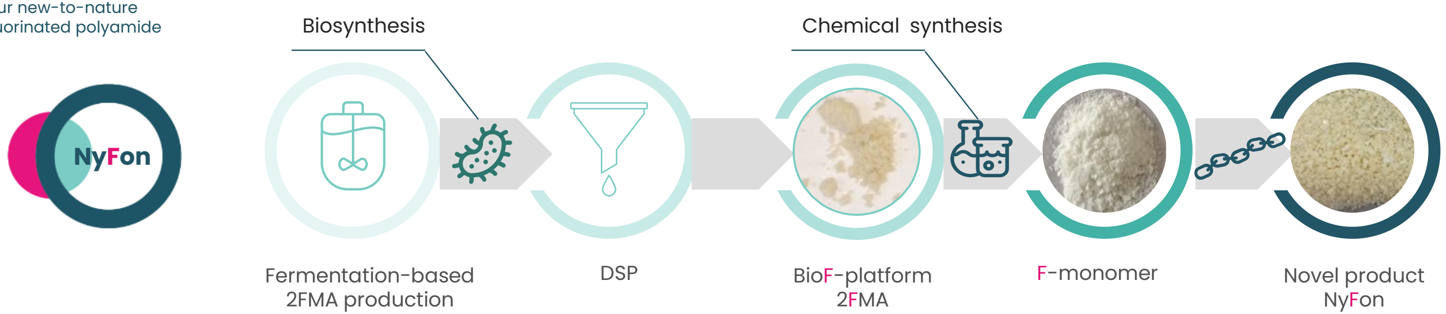
Product 1: F-PHB

- Our flagship molecule and Teflon replacement



Product 2: NyFon

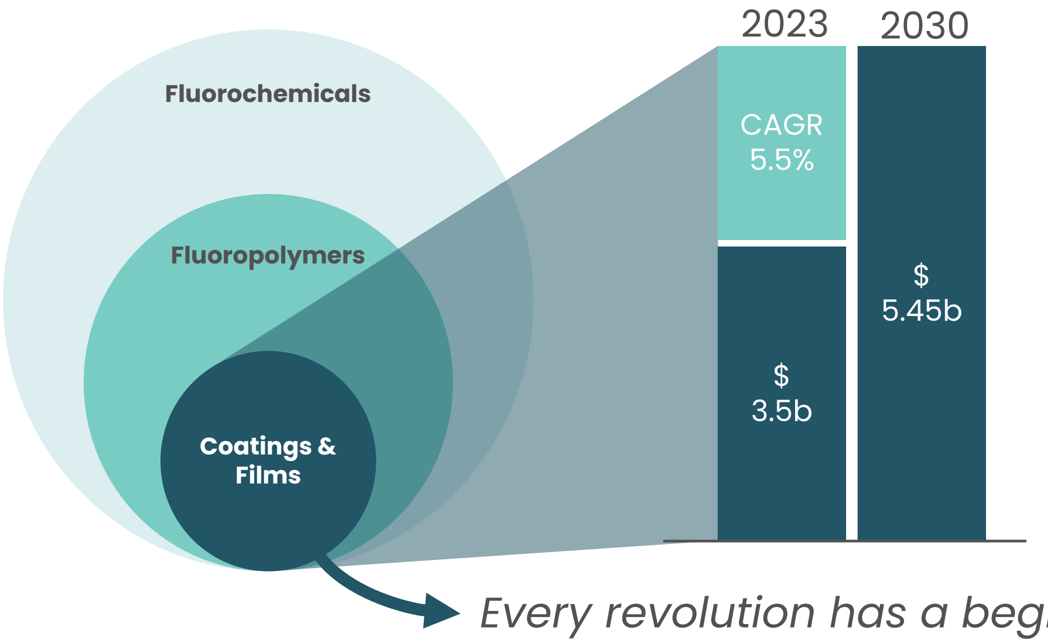
- Our new-to-nature fluorinated polyamide



PFAS coatings and films offer high potential as a beachhead market due to its size and potential for low volume and high price

PFAS market segments

Market Growth Projection



Every revolution has a beginning!

BioHalos approach to the market

- The PFAS market can be divided in three segments based on the product form:
  - Coatings & films (beachhead)
  - Fluoropolymers
  - Fluorochemicals
- Market incumbents consist to a large extent of global manufacturers with high production volumes at low cost
- Coatings and films are typically applied in thin layers, and requires low volumes
- In the coating and film segment, there are many potential buyers PFAS is a low share of their total cost, which make them less price sensitive
- BioHalo has identified the coatings and films market as a high potential beachhead market, as they can compete on performance and sustainability rather than high volumes and low cost
- In time, and with scale, BioHalo expects to reduce their production costs considerably, and sees a potential to enter the other market segments, first fluoropolymers, and later fluorochemicals

We are at the center of the attention

Awards

Awards from several well renowned actors underline the faith market experts put in our company.

JEC — CONNECTING THE WORLD WITH COMPOSITES › Sustainable impact startup / Startup Booster 2024 winner

SYN BEE › Winner of SynBio Startup competition

Nucleate › Investor Prize by BlueYard Capital

Programs

With support from some of the biggest programs on the market, we are set up for success.

Amplifier › Access to EYs collected expertise through 300 hours of free consultancy

BII › Transforming life science startups with funding, expertise, and global networks.

Nucleate Denmark › Program empowering biotech founders with resources, mentorship, and community.

iNAM › Accelerating advanced materials startups through tailored support and industry connections.

PLUGANDPLAY JAPAN › Connecting startups with major Japanese corporations and SMEs.

Events

Through events, we keep expanding our brand and increase interest from potential partners, investors and customers across the globe.

European Chemistry Partnering

BOOST PITCH PERFECT the EUROPEAN BIOECONOMY 2023

Nordic Innovation Fair — Business Opportunities from Nordic Research Institutions

hello tomorrow

ICOS CAPITAL Collaborative Summit

BioHalo

The biohalogenation company

Support us in our Revolution!

BioHalo

Get in touch with us!

BioHalo

nico@biohalo.io

johann@biohalo.io

Supported by

iNAM · iGEM EPIC · Nucleate Denmark · PLUG AND PLAY JAPAN · Amplifier

Funded by

BII · Innovationsfonden · Defence and Security Accelerator · BLUE YARD

UCL

PFAS-free Robust Liquid-repellent Surfaces from Reticular Frameworks

Priya Mandal (Ph.D.)

(Prof. Manish K Tiwari and Team)

Nanoengineered Systems Laboratory

University College London, London, U.K.

European Research Council
Established by the European Commission

EPSRC
Engineering and Physical Sciences Research Council

THE ROYAL SOCIETY

wellcome

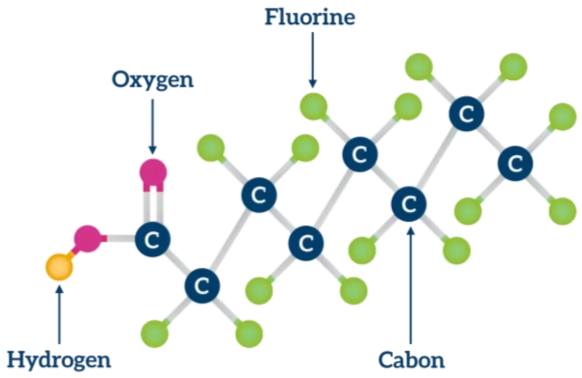
ROYAL ACADEMY OF ENGINEERING

UCLB

PFAS-free Coatings

What are PFAS?

Per- and polyfluoroalkyl substances (PFAS) – a group of around 8,000 synthetic chemicals – used in a variety of industries around the globe since the 1940s.



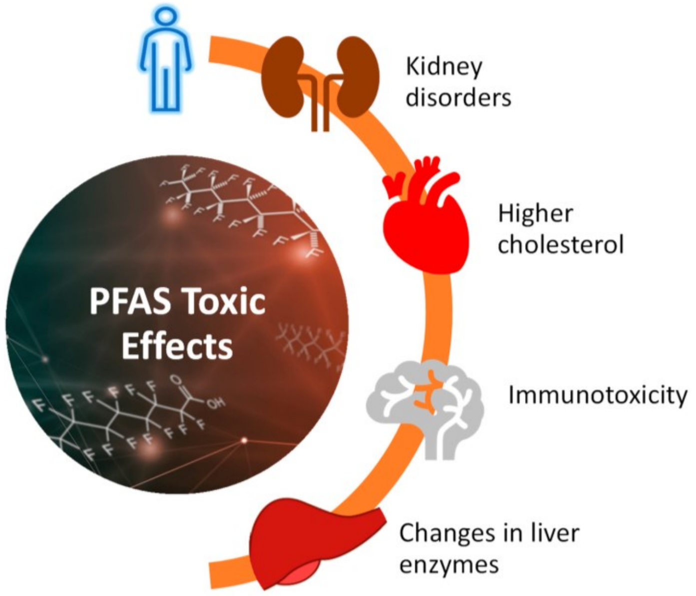
The carbon-fluorine bond is extremely strong and stable.

Where are these used?

Originally manufactured for firefighting foams to help extinguish petroleum fires.

Effect on human health

PFAS are extremely toxic.
Just 1 soda can's worth can contaminate over 42 billion liters of water.



Government regulations?

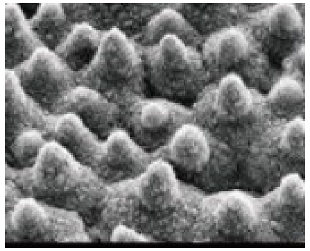
- The European Chemicals Agency (ECHA) has proposed listing some PFAS substances as "substances of very high concern" to limit their use across industries.
- The U.S. Environmental Protection Agency (EPA) has established a health advisory for PFAS in drinking water, recommending levels below 70 parts per trillion.

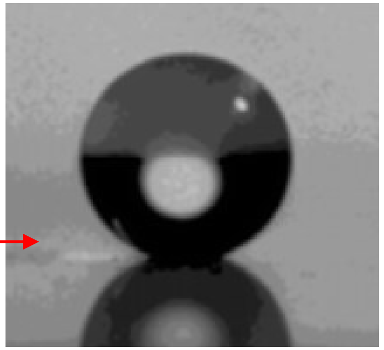
Pollutants, 4(1), pp.136-152, 2024

Nature-inspired Liquid-repellent Surfaces

Superhydrophobic surfaces (SHS)

Lotus leaf

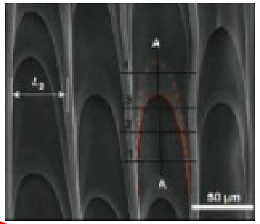


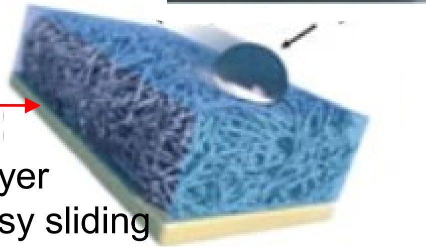


- Micro/nano structure
- Low surface energy
- Low adhesion
- **Mechanically fragile**

Slippery liquid-infused porous surfaces (SLIPS)

Nepenthes





- Nano groove/pore
- Slippery lubricant layer
- Oil-repellent and easy sliding
- **Lubricant depletion**

Applications:

Self-cleaning

Deicing

Anti-fogging

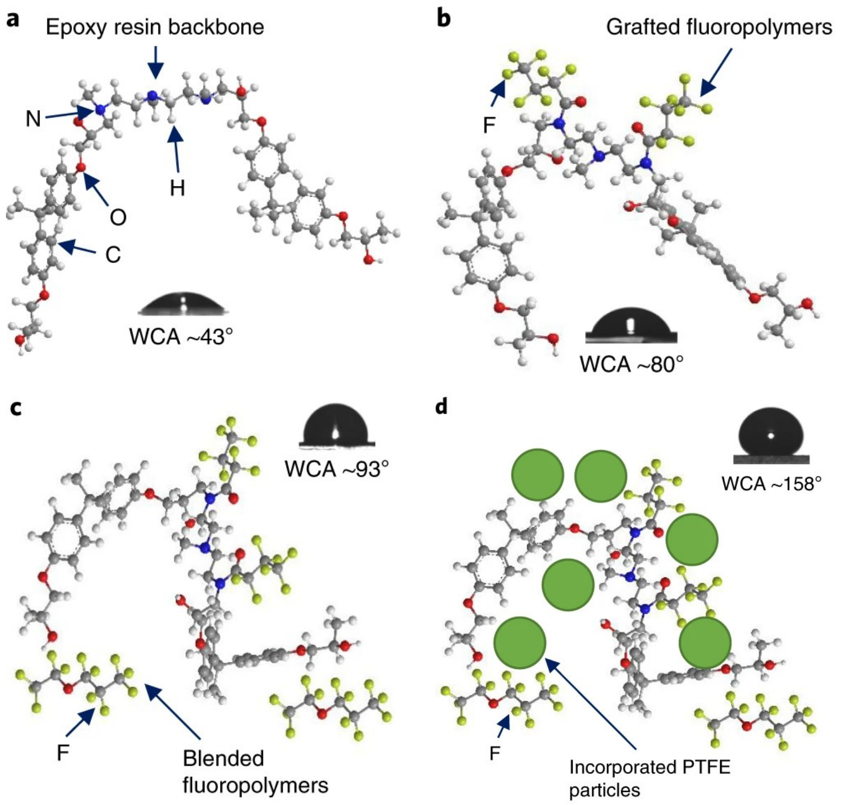
Condensation enhancement

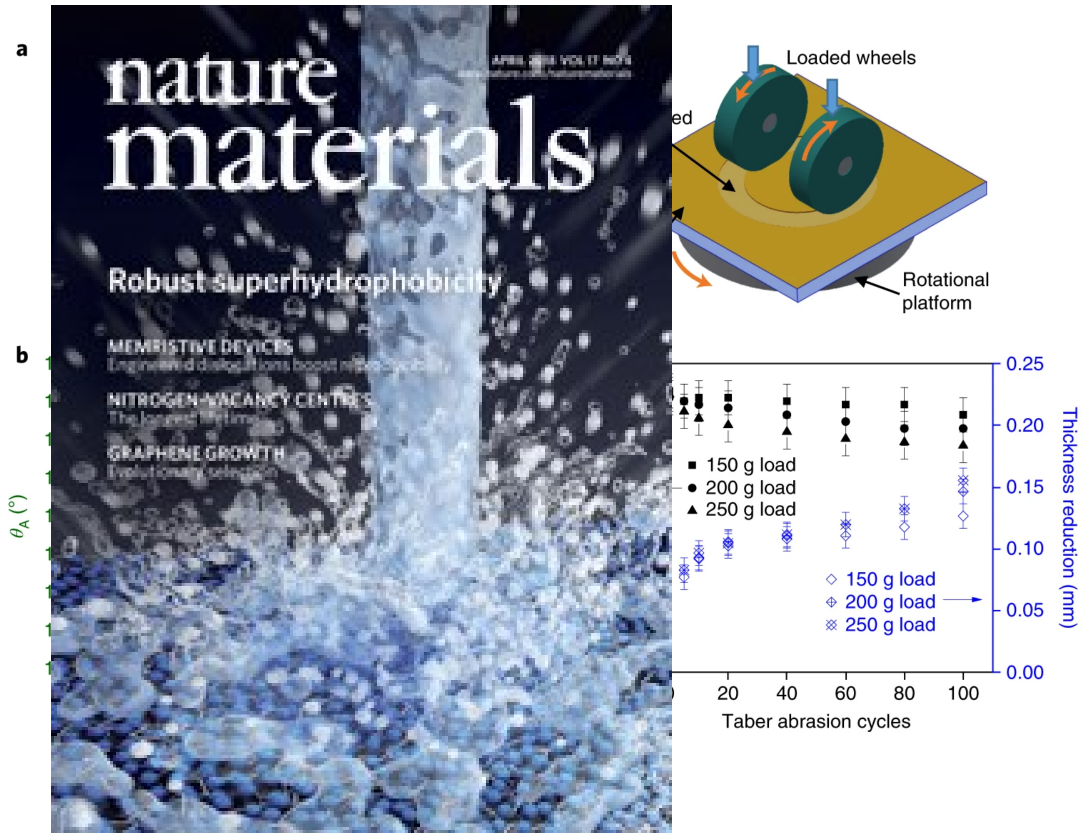
Anti-biofouling

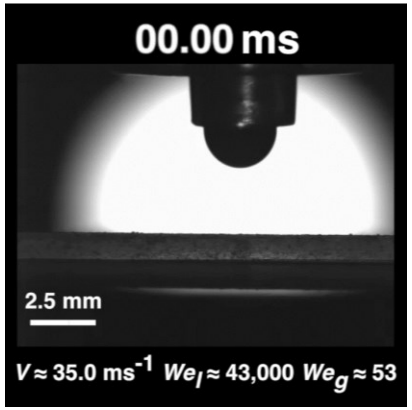
Anti-corrosion

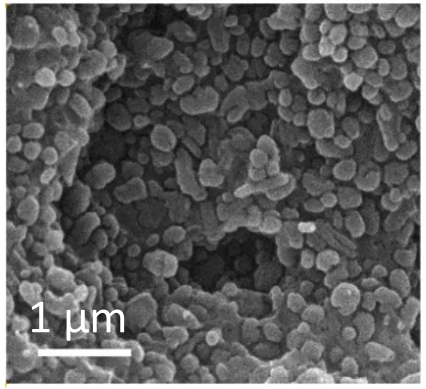
Chemical Society Reviews, 36(8), pp.1350-1368, 2007; Nature, 477(7365), pp.443-447, 2011

Nanoengineered Surfaces: Mechanochemical Robustness and Impalement Resistance









- All-organic flexible superhydrophobic coating
- Mechanical robustness under tape peel and Taber abrasion
- Mechanical flexibility – High-speed jet impact resistance
- Chemical resistance – Aquaregia and sodium hydroxide solutions

Nature Materials, 17(4), pp.355-360, 2018

Current achievement:

- All-organic superhydrophobic surface with mechano-chemical robustness and impalement resistance
- Fluorine-based micro/nano roughness to achieve low surface energy

Key issues:

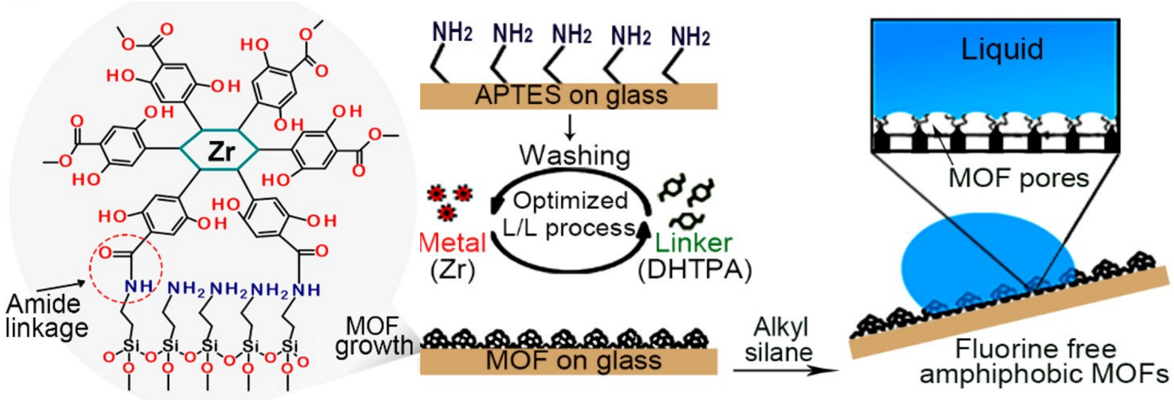
- Fluorine dependence poses environmental and regulatory concerns
- Only repel water, fails to achieve amphiphobicity

Our strategy: Nanohierarchical porous network

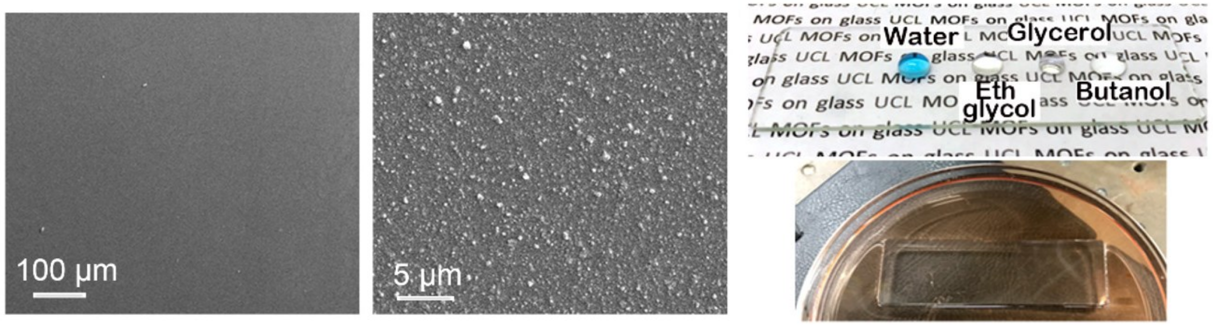
Metal/covalent Organic Frameworks (MOF/COF)

- Highly tunable porosity with precise nanostructuring
- Reticular chemistry enables controlled surface functionality
- High capillary pressure due to sub-nanometer pores, beneficial for amphiphobicity
- Potential for fluorine-free alternatives with superior liquid repellency

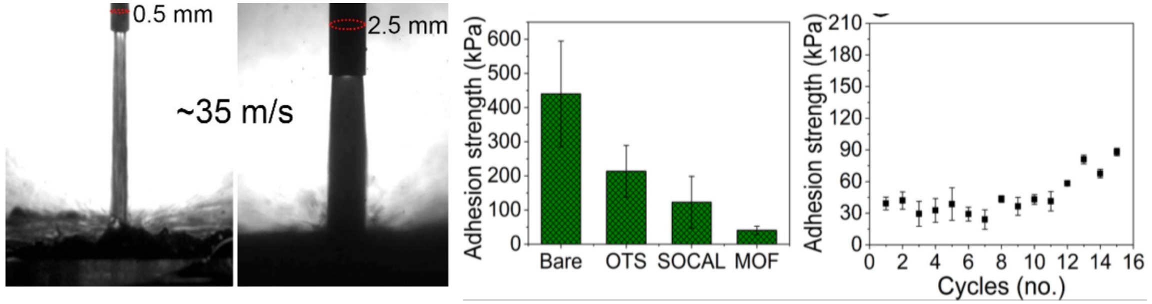
Nanohierarchical Surface-grown Metal-Organic Frameworks (MOF)

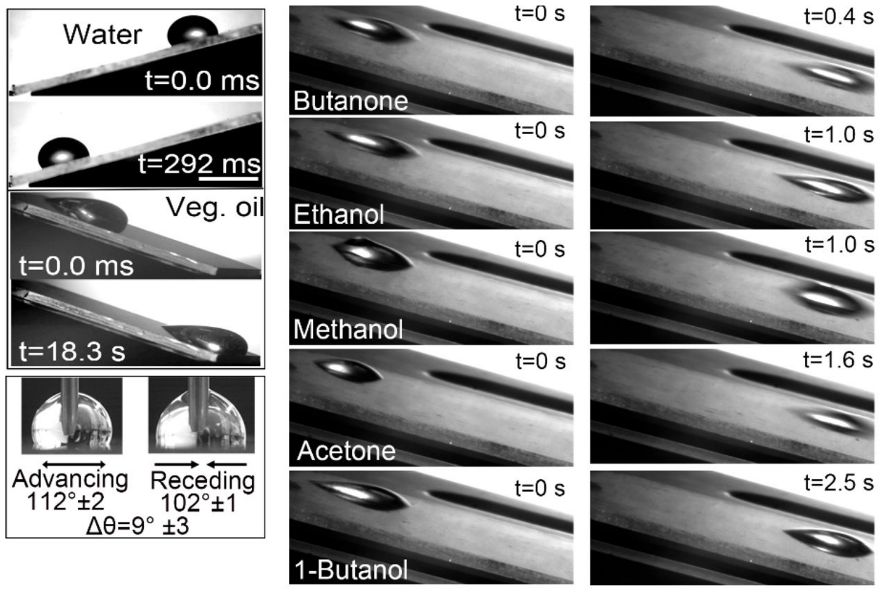


A thin layer of UiO-66 (Zr-MOF) grown on glass



Film thickness ~ 200 nm, Roughness ~ 70 nm



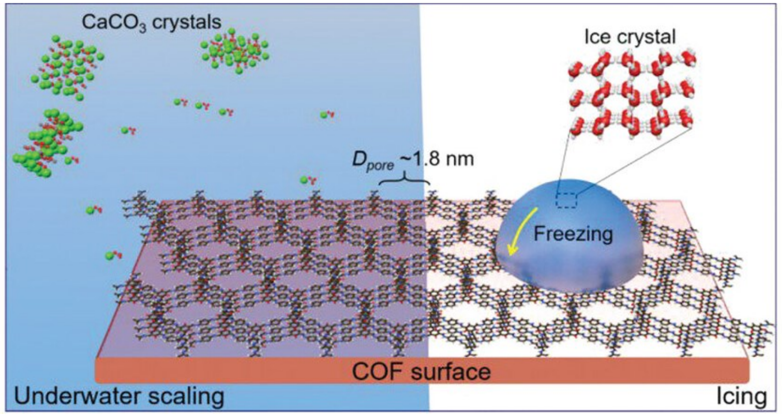


Repel low-surface tension liquids – Amphiphobicity

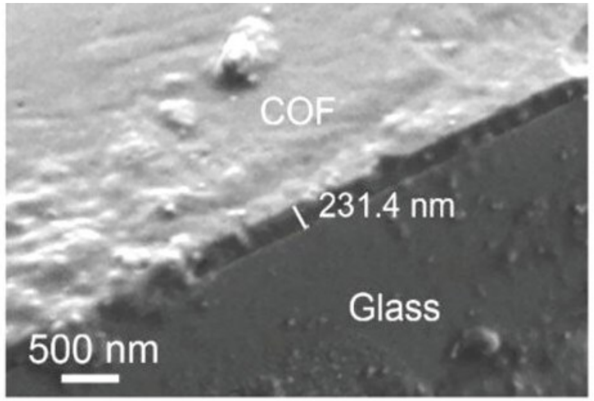
- **Self-cleaning:** Flexible alkyl chains enable low drop sliding angles.
- **Transparent and durable:** ~200 nm MOF films offer optical clarity and robustness.
- **Extreme resilience:** Withstands high-speed impact, heat (200°C), scratches, and chemicals.
- **Multifunctional:** Reduces ice adhesion and removes water pollutants.

Nano Letters, 21(8), pp.3480-3486, 2021

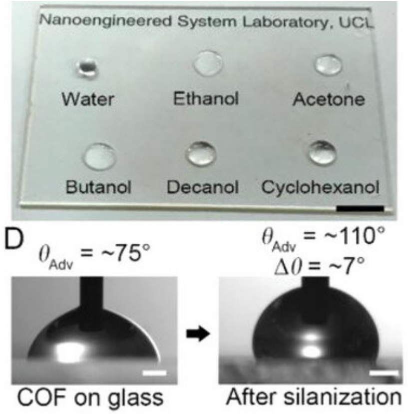
Transparent Anti-(icing/fouling) Covalent-Organic Frameworks (COF)



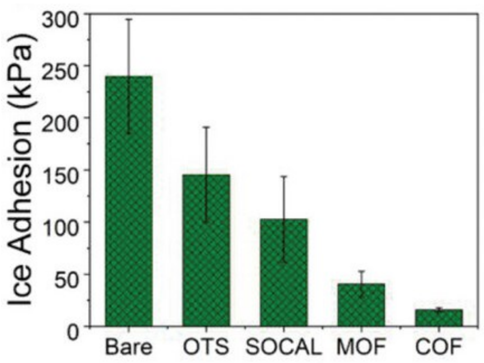
Defect-free growth – Interfacial polymerisation

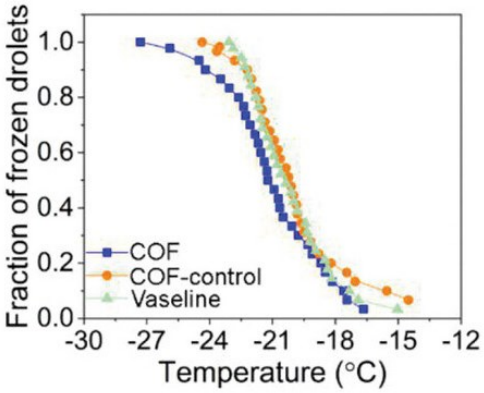


Thickness ~ 200 nm



Amphiphobicity

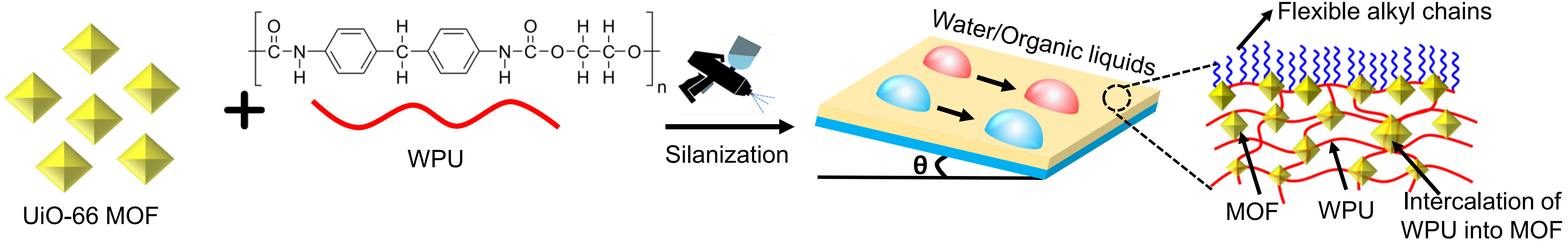


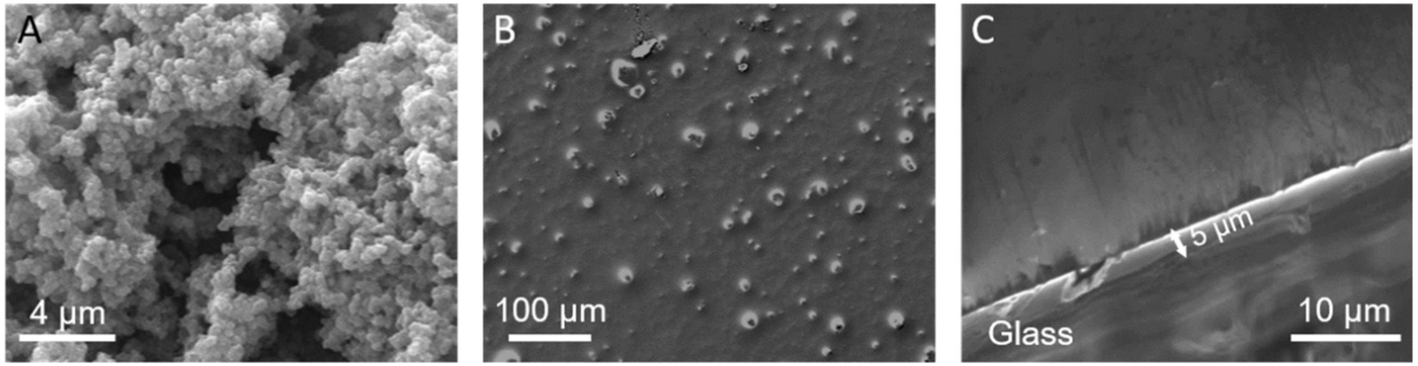


- **Ice and scale prevention:** COF-based nanocoatings delay ice nucleation (-28°C) and prevent scale formation (>2 weeks) in harsh conditions
- **High performance and durability:** Resistant to organic solvent jets (Weber > 10^5) while maintaining optical transparency (>92%).
- **Sustainable and scalable:** Fluorine-free, defect-free COFs leverage nanoconfinement for long-term, real-world applicability.

Advanced Materials, 35(38), p.2302466, 2023

Intercalated MOF Nanocomposite – Waterborne Amphiphobicity



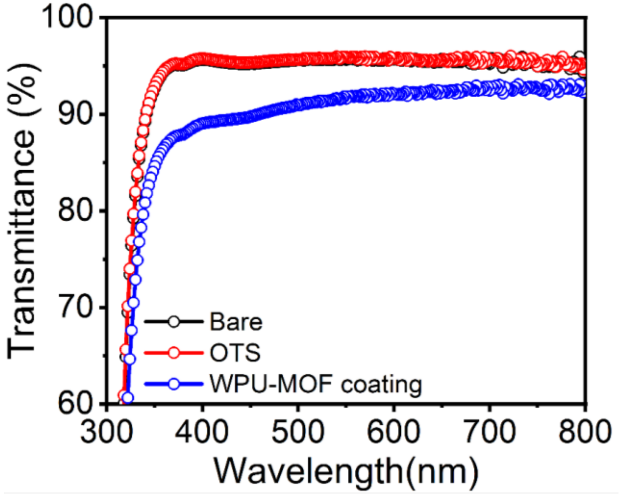


MOF nanoparticles ~ 300 nm

Film thickness ~ 5 μm

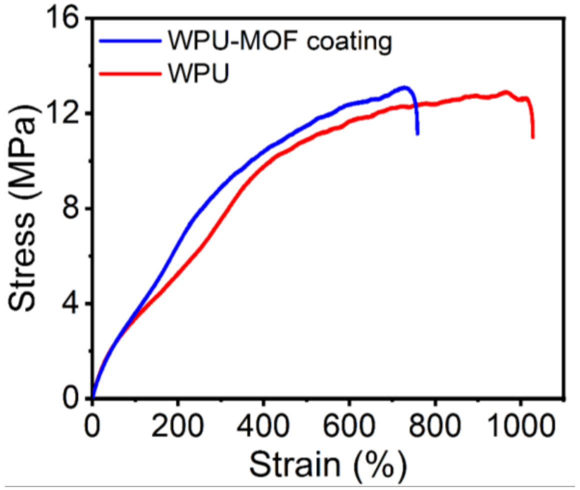
- **Water-based** spray formulation for easy application
- Polymer-particle **intercalated nanocomposite** enhances performance
- **Compatible with various substrates** for broad applicability
- **Scalable** process for real-world implementation

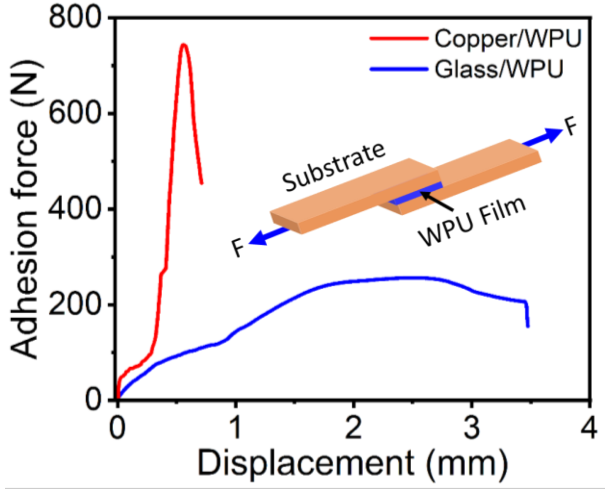
Optical transparency:



- 91% transparency with low local roughness
- Maintains clear visibility of text beneath the coating
- Repels low surface tension liquids

Mechanical properties:

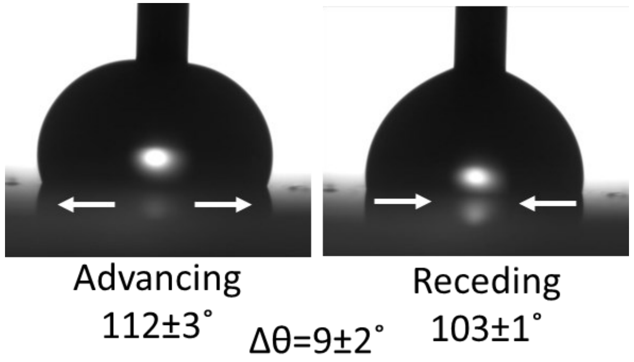


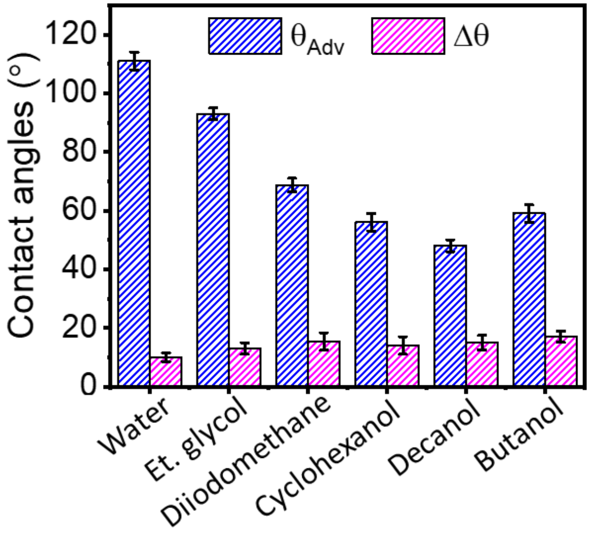


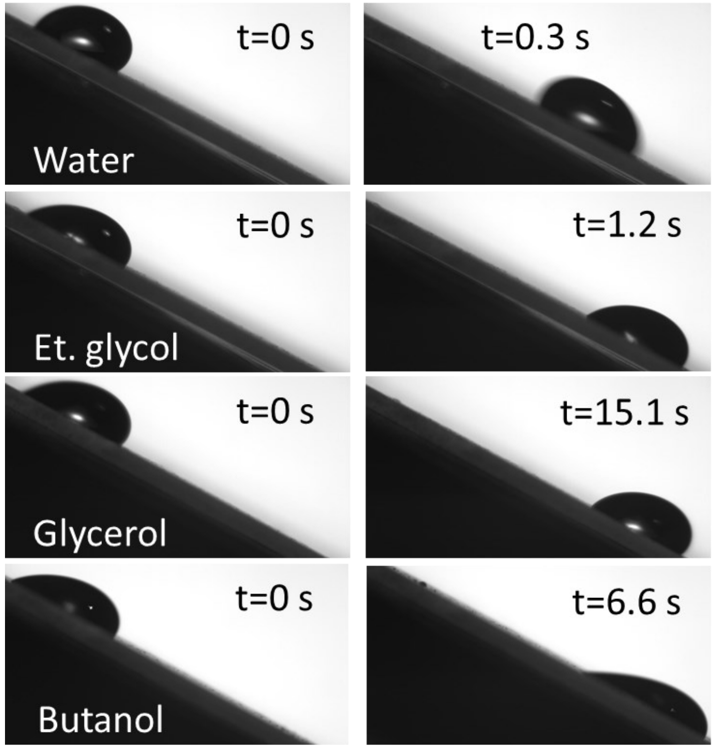
- Elongation at break ~ 758%, Toughness ~ 94.3 MJ m^{-3}
- Interfacial bonding strength ~ 1.9M Pa (copper) and 0.5 MPa (glass)

Environ. Sci.: Nano, 2025

Wetting behaviour – Amphiphobicity



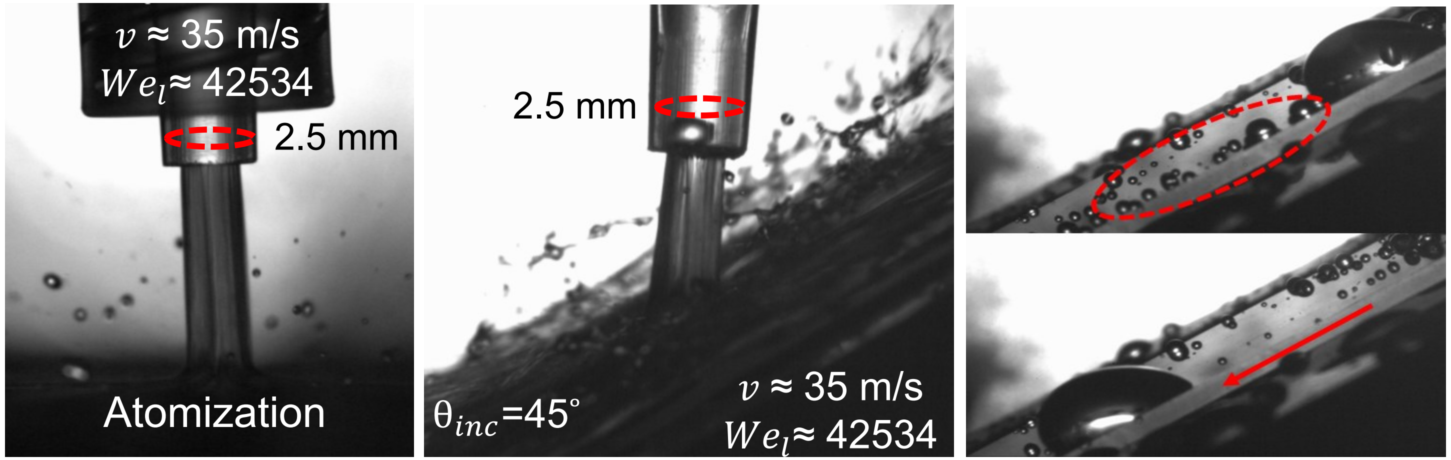




Sliding of low surface tension liquids

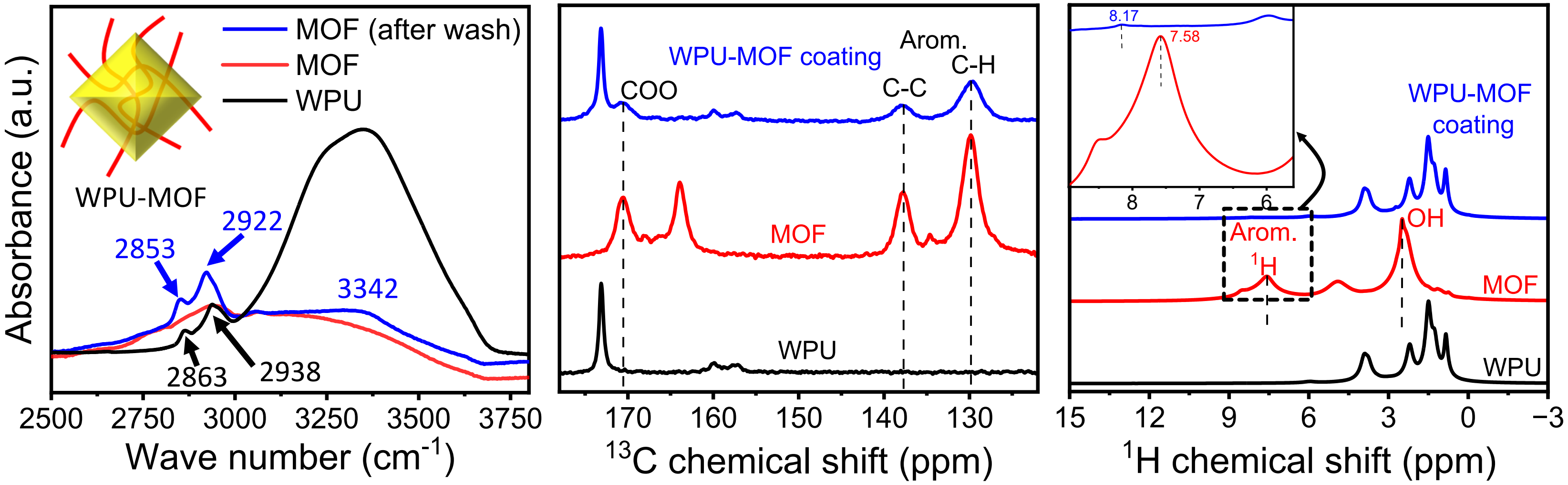
- WPU-MOF coating is smooth and highly amphiphobic
- Water shows θ_{Adv} ~112°, Δθ ~9°, and slides off at <30° tilt
- MOF nanostructure and silane functionalization improve repellency.

Impalement resistance:



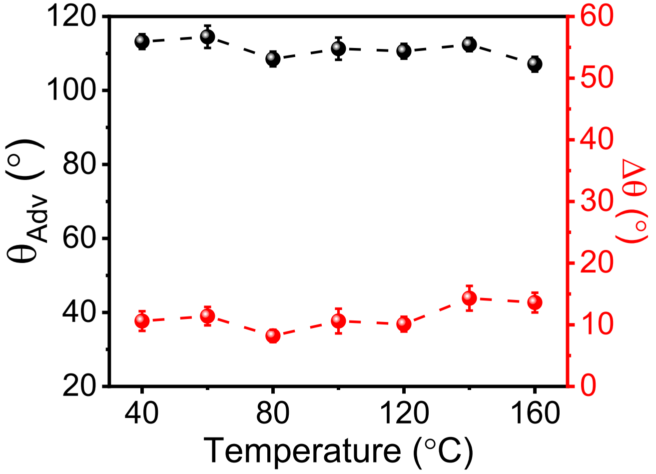
- Intercalation of polymer into MOF pores – Bicontinuous structure

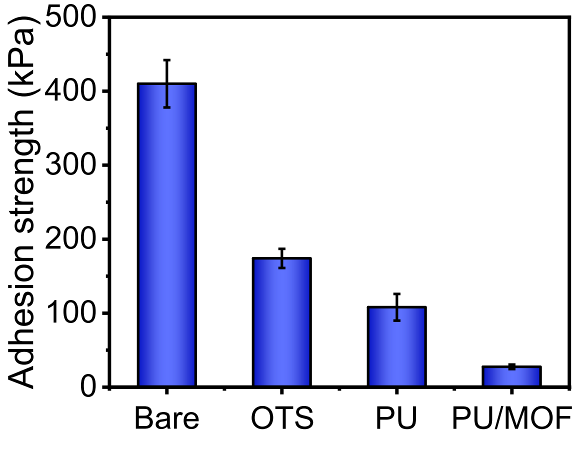
Intercalation of polymer into MOF:

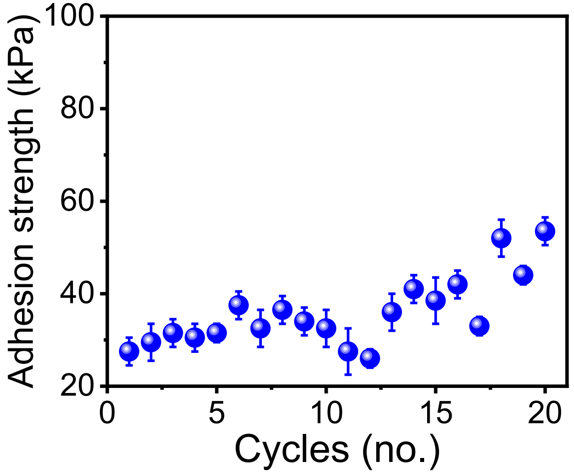


Environ. Sci.: Nano, 2025

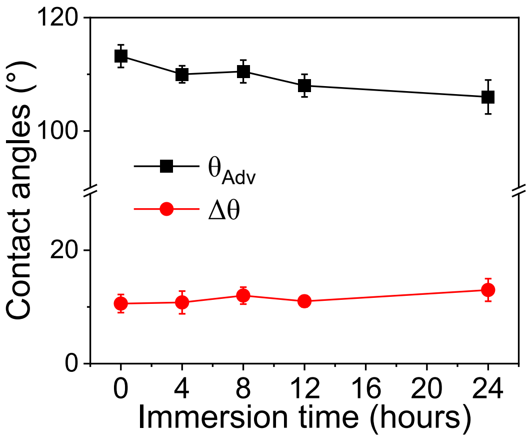
Thermal stability and anti-icing performance:

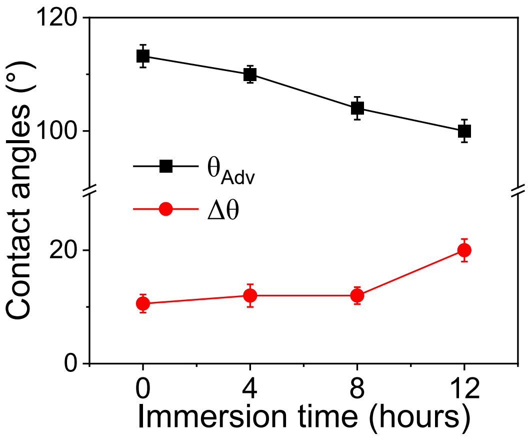






Chemical resistance:





Environ. Sci.: Nano, 2025

Conclusions:

Scalable and fluorine-free: Water-based, spray-based formulation

Strong adhesion and durability: WPU intercalation in MOF pores enhances mechanical robustness

Superior amphiphobicity: Effective liquid repellency (surface tension as low as 25 mN/m)

Multifunctional performance: Thermal stability, impact resistance (35 m/s jet), and anti-icing (~30 kPa adhesion)

Industrial potential: Robust, eco-friendly coatings

Future improvement: Need to simplify the two-step post-functionalization process

UCL MECHANICAL ENGINEERING

wellcome EPSRC centre interventional + surgical sciences

Thank you for your kind attention !

Contact: priya.mandal@ucl.ac.uk

GREEN TECHNOLOGIES AND PFAS ALTERNATIVES

Dr. SHUBHI SHARMA

SCIENTIFIC RESEARCH ASSISTANT

CHEM Trust

Shubhi.Sharma@chemtrust.org

CHEM Trust

Protecting humans and wildlife from harmful chemicals

- Environmental and health charity working at UK, EU & Global levels to protect humans & wildlife from harmful chemicals
- Working with scientists, technical processes and decision makers, in partnership with other NGOs

Website: chemtrust.org

LinkedIn: CHEM Trust

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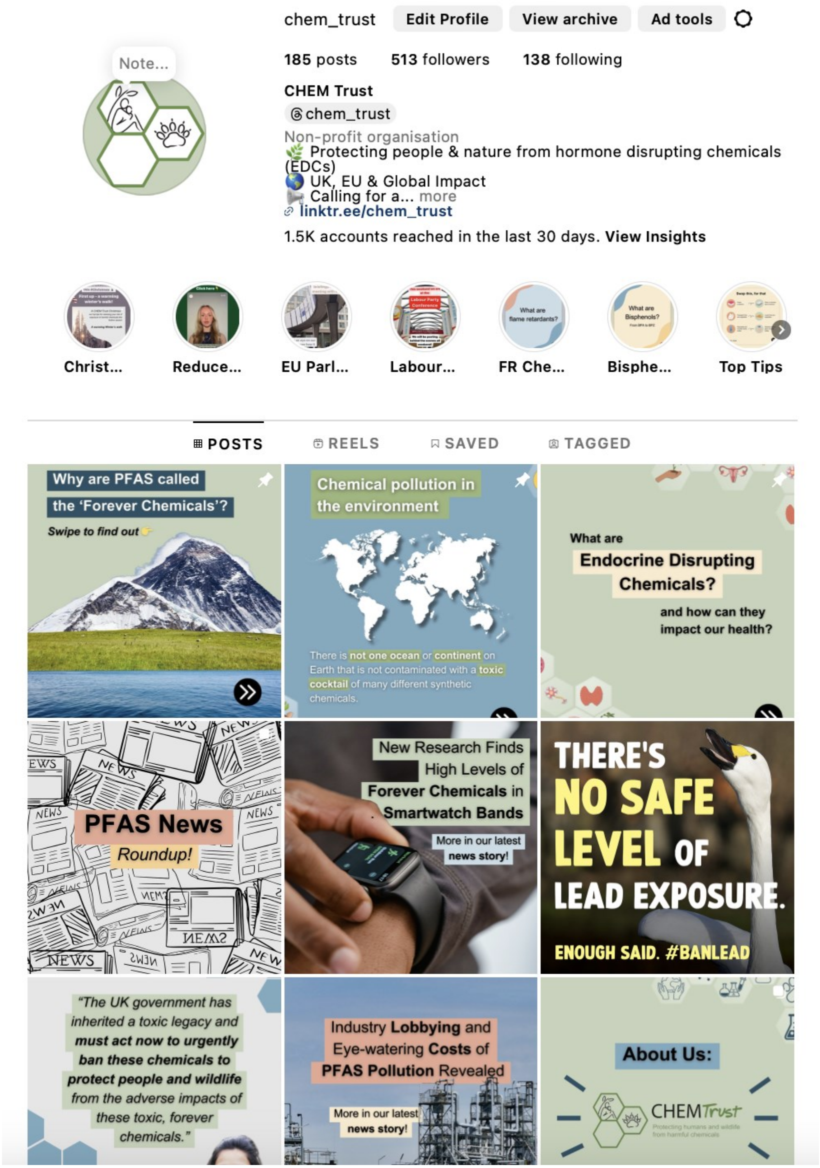

Information provided is solely based on the research that we have done, and we have no commercial ties with the companies.

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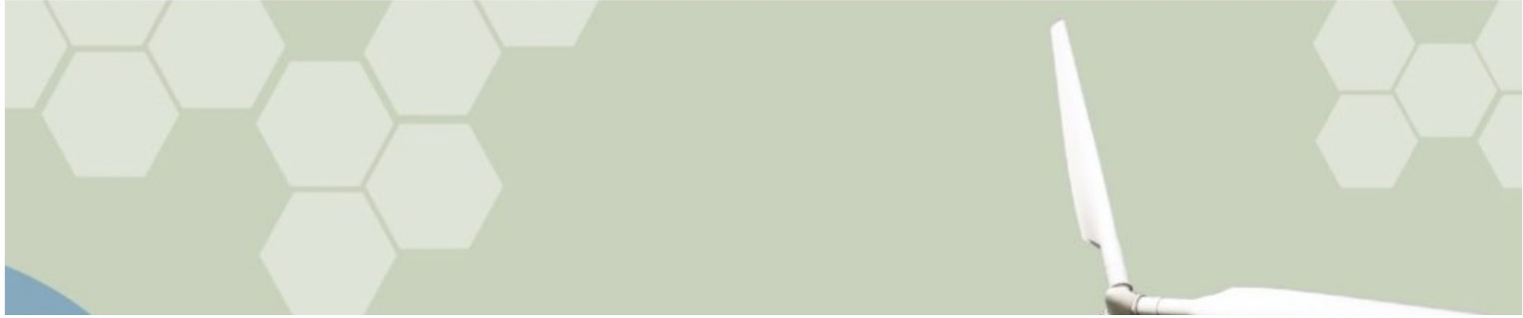
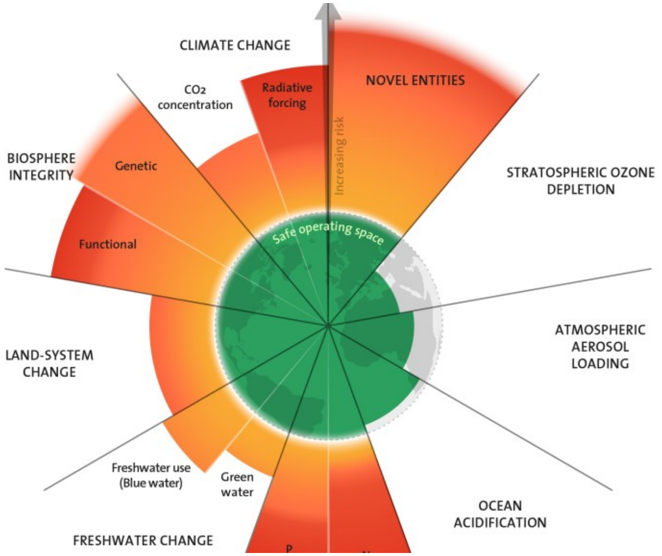
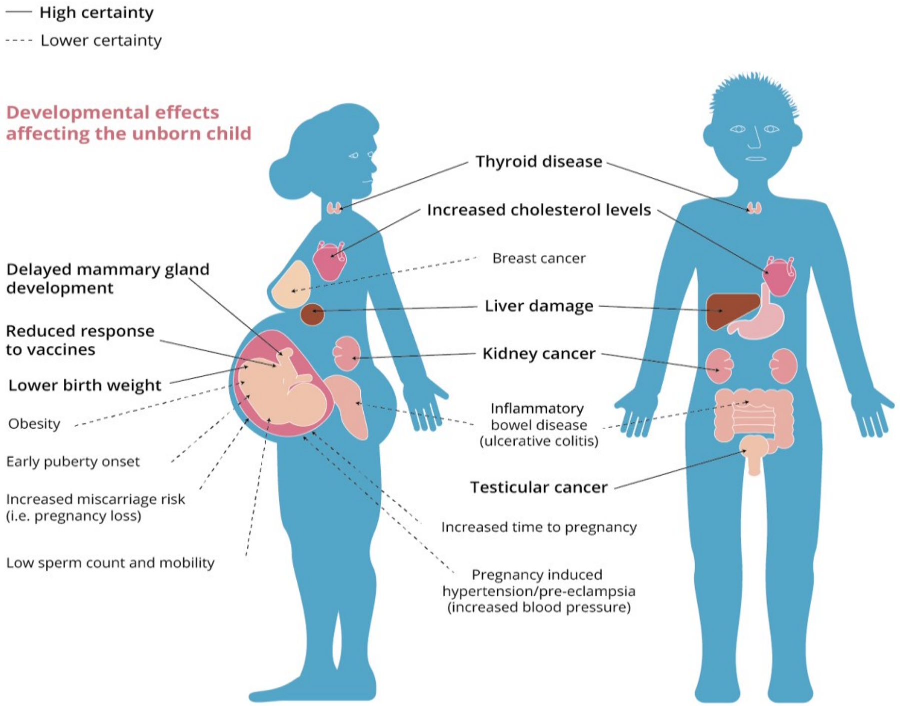
Can we transition to a green economy and deal with the PFAS pollution crisis?

July 3, 2024 By **Anna Watson**





Azote for Stockholm Resilience Centre, based on analysis in Richardson et al 2023



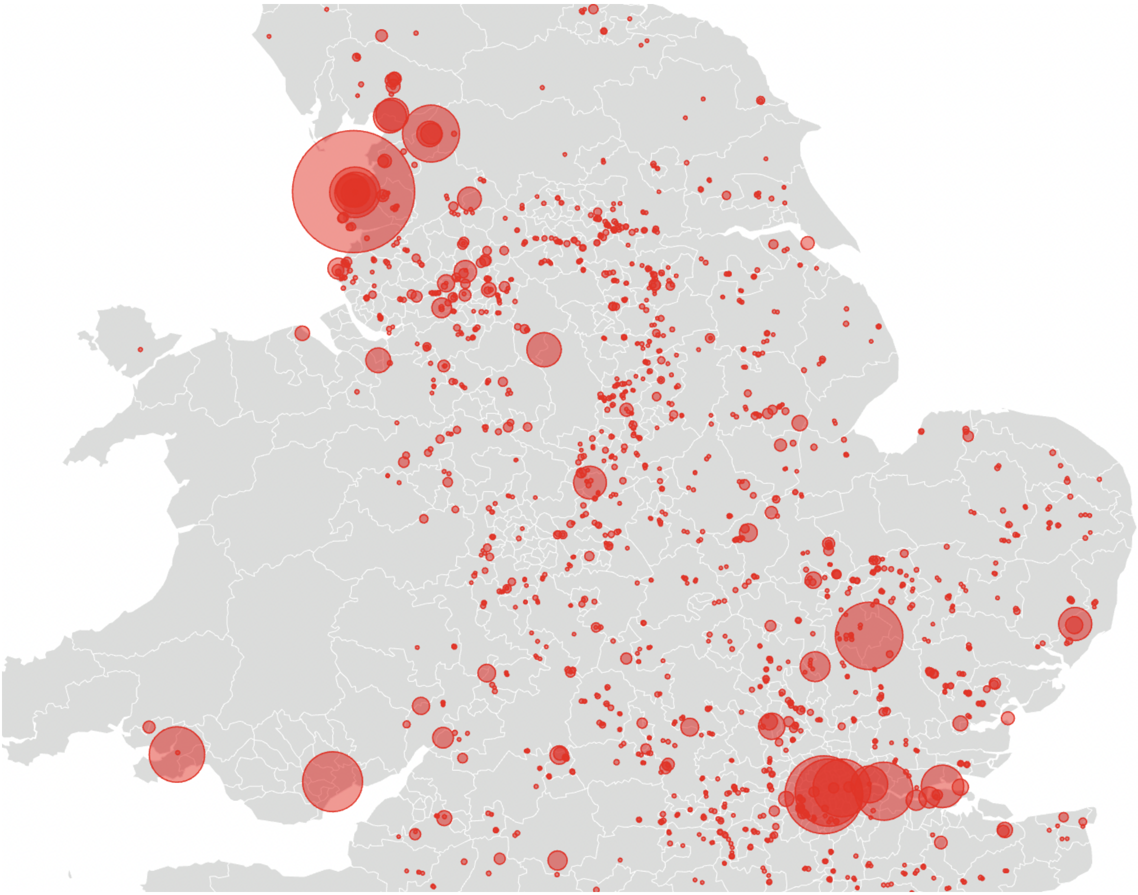
C8 health project reports 2012, US national toxicology program 2016,

WHY ARE PFAS A PROBLEM?

- PFAS pollution has crossed the planetary boundary for novel entities (Cousins et al, 2022).

- Exposure to some PFAS may cause **kidney and testicular cancers**, **reduced vaccination efficiency** in children, **interference** with the **reproductive system,** the **development of the foetus** and with our **hormonal system.**

- Need to learn lessons from the past i.e. PCBs - - although banned – almost impossible and very costly to remove once they reach environmental sinks i.e. the ocean (Šrédlová and Tomáš, 2022) .



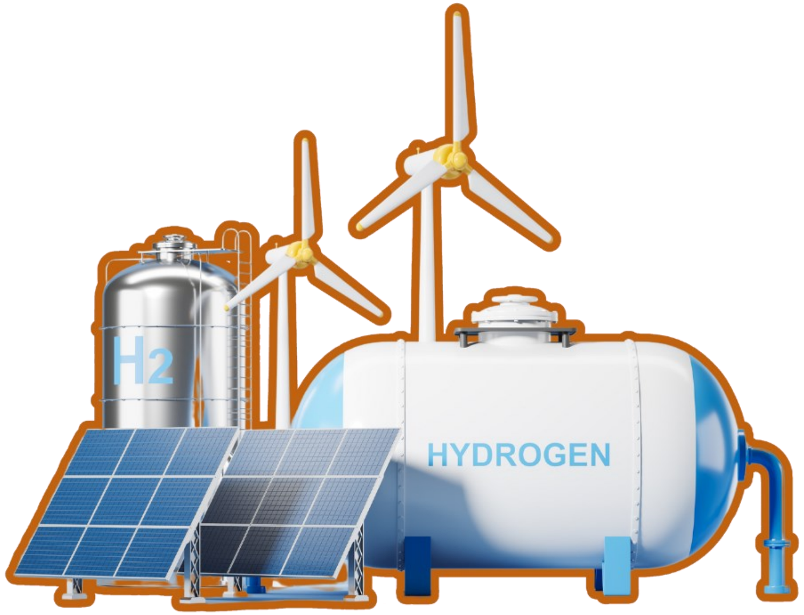
Royal Society of Chemistry PFAS / constituencies and population

THE COST OF INACTION ON PFAS POLLUTION IS ENORMOUS

- The RSC map shows **thousands of PFAS hotspots** in the UK.
- £1.6tn– cost of PFAS remediation in the UK and EU (Forever Lobbying Project, 2025).
- EA has warned it lacks the budget to tackle rising number of PFAS hotspots.
- Some industry say that PFAS alternatives are not available for green transition technologies - **this is incorrect.**

PFAS ALTERNATIVES IN GREEN HYDROGEN AND SOLAR TECHNOLOGIES

- Both technologies use fluoropolymers.
- **Fluoropolymers are NOT chemicals of low concern.** They emit various other harmful PFAS (like PFOA, Gen X, Adona) during production, use and disposal (Lohmann et al, 2020, Lang et al, 2016, Eggen et al, 2010).
- Fluoropolymer-free solutions for green hydrogen and solar panels are being marketed by several companies (**Ionomr, Solarge, Endurans**).



PFAS ALTERNATIVES IN ELECTRIC VEHICLE BATTERIES

- Lithium-ion batteries also currently use fluoropolymers.

- Companies like **Leclanché, Cellfion, GRST, BeFC, E-lyte and Nanoramic** offer solutions to eliminate PFAS from Lithium-ion batteries.

PFAS ALTERNATIVES IN REFRIGERANTS

- Refrigerants use Hydrofluoroolefins (HFOs), which are F-gases.
- HFOs break down into TFA - very persistent and mobile PFAS. Germany intends to recommend it as a **reprotoxic substance.**
- Propane (domestic). CO2 and NH3 (commercial). Marketable end economically feasible.
- Volkswagen have committed to replace PFAS refrigerants in their vehicles for air con and battery cooling.
- More info: https://naturalrefrigerants.com/coalition-for-pfas-free-cooling-heating-is-launched/

CONCLUSION

- Green transition can happen without the use of PFAS.
- The **cost of inaction** on PFAS is **much higher** than any cost that might come with PFAS regulation.
- A green transition that contributes to the already existing PFAS crisis cannot really be called a green transition.
- A **universal ban on PFAS** is the only way to control the PFAS pollution disaster.


ROYAL SOCIETY OF CHEMISTRY

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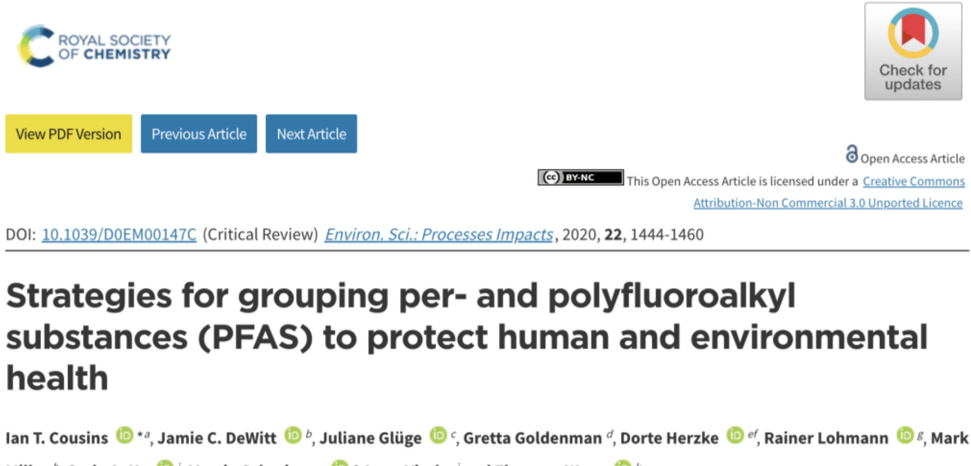
DOI: 10.1039/D0EM00355G (Perspective) *Environ. Sci.: Processes Impacts*, 2020, **22**, 2307-2312

The high persistence of PFAS is sufficient for their management as a chemical class

Ian T. Cousins [*a], Jamie C. DeWitt [b], Juliane Glüge [c], Gretta Goldenman [d], Dorte Herzke [ef], Rainer Lohmann [g], Carla [h], Martin Scheringer [c] and Zhanyun Wang [i]


ROYAL SOCIETY OF CHEMISTRY

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DOI: 10.1039/D0EM00147C (Critical Review) *Environ. Sci.: Processes Impacts*, 2020, **22**, 1444-1460

Strategies for grouping per- and polyfluoroalkyl substances (PFAS) to protect human and environmental health

Ian T. Cousins [*a], Jamie C. DeWitt [b], Juliane Glüge [c], Gretta Goldenman [d], Dorte Herzke [ef], Rainer Lohmann [g], Mark

The Impact of PFAS Regulations on Membrane Materials for PEM Fuel Cells

Maia Benstead - Technology Analyst, IDTechEx

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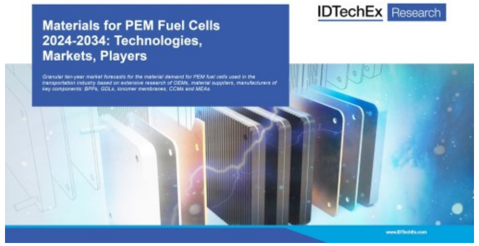
Sample pages are available for all reports available at www.IDTechEx.com. For more information, contact research@IDTechEx.com.

H_2 Production	Materials	Fuel Cells & Mobility	Entire Value-Chain

Green Hydrogen Production & Electrolyzer Market 2024-2034

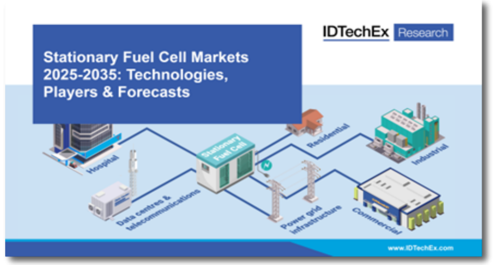
Blue Hydrogen Production and Markets 2023-2033



Materials for PEM Fuel Cells 2024-2034

Materials for Green Hydrogen Production 2024-2034

Hydrogen Internal Combustion Engines 2025-2045



Stationary Fuel Cells 2025-2035

Battery Electric & Hydrogen Fuel Cell Trains 2023-2043

Fuel Cell Boats & Ships 2023-2033

Fuel Cell Electric Vehicles 2024-2044

Hydrogen Economy 2023-2033: Production, Storage, Distribution & Applications

Sustainable Future Aviation 2025-2045

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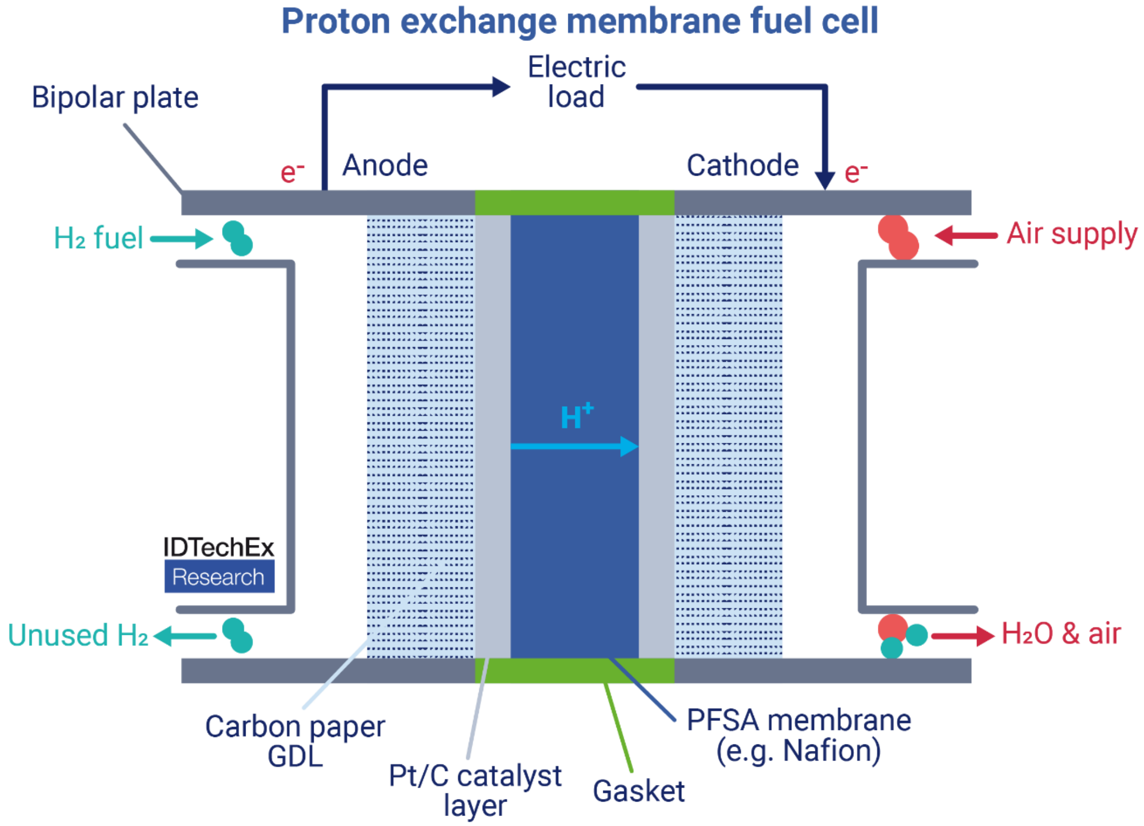
Understanding PEMFCs: Working Principle

Molecular hydrogen and oxygen are pumped into flow fields on either side of the fuel cell. The hydrogen is pumped into the anode flow field, while oxygen is pumped into the cathode flow field.

Both gases pass through a gas diffusion layer and reach a catalyst layer. This catalyst typically contains platinum and helps to strip the hydrogen of electrons, leaving behind protons.

The electrons travel from the fuel cell to the load to do electrical work. Protons pass through the proton exchange membrane.

On the cathode side, the protons recombine with oxygen gas to produce water, the main by-product of PEMFC operation.



Anode: $2H_2(g) \rightarrow 4H^+ + 4e^-$

Cathode: $O_2(g) + 4H^+ + 4e^- \rightarrow 2H_2O$

Cell: $2H_2 + O_2 \rightarrow 2H_2O$

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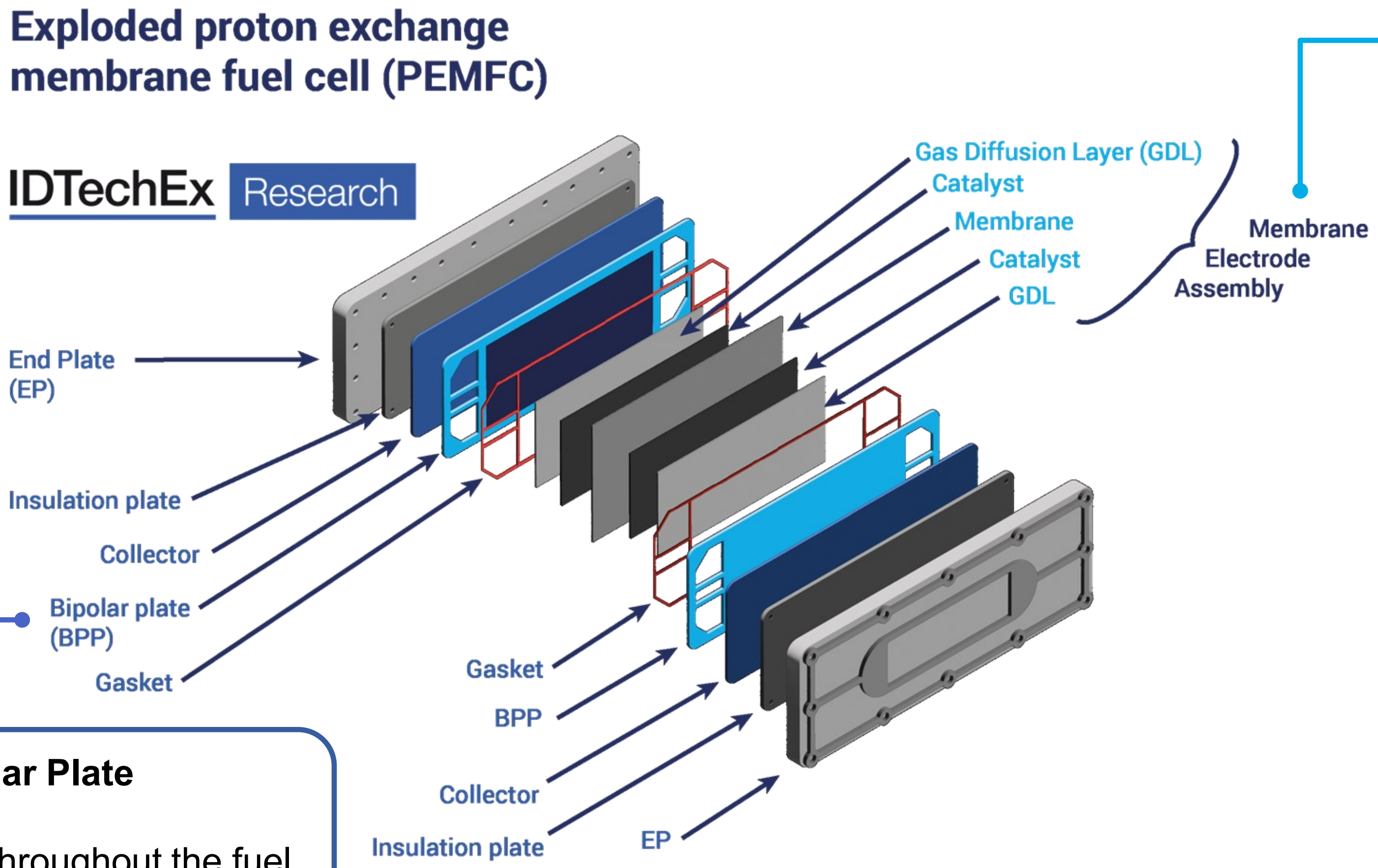
Understanding PEMFCs: Major Components



Membrane Electrode Assembly

Gas Diffusion Layer

A porous medium facilitating the transfer of reactants (hydrogen, oxygen) and products (water) to and from the catalyst layer.

Catalyst

Plays a key role in facilitating the chemical reactions that occur within a fuel cell

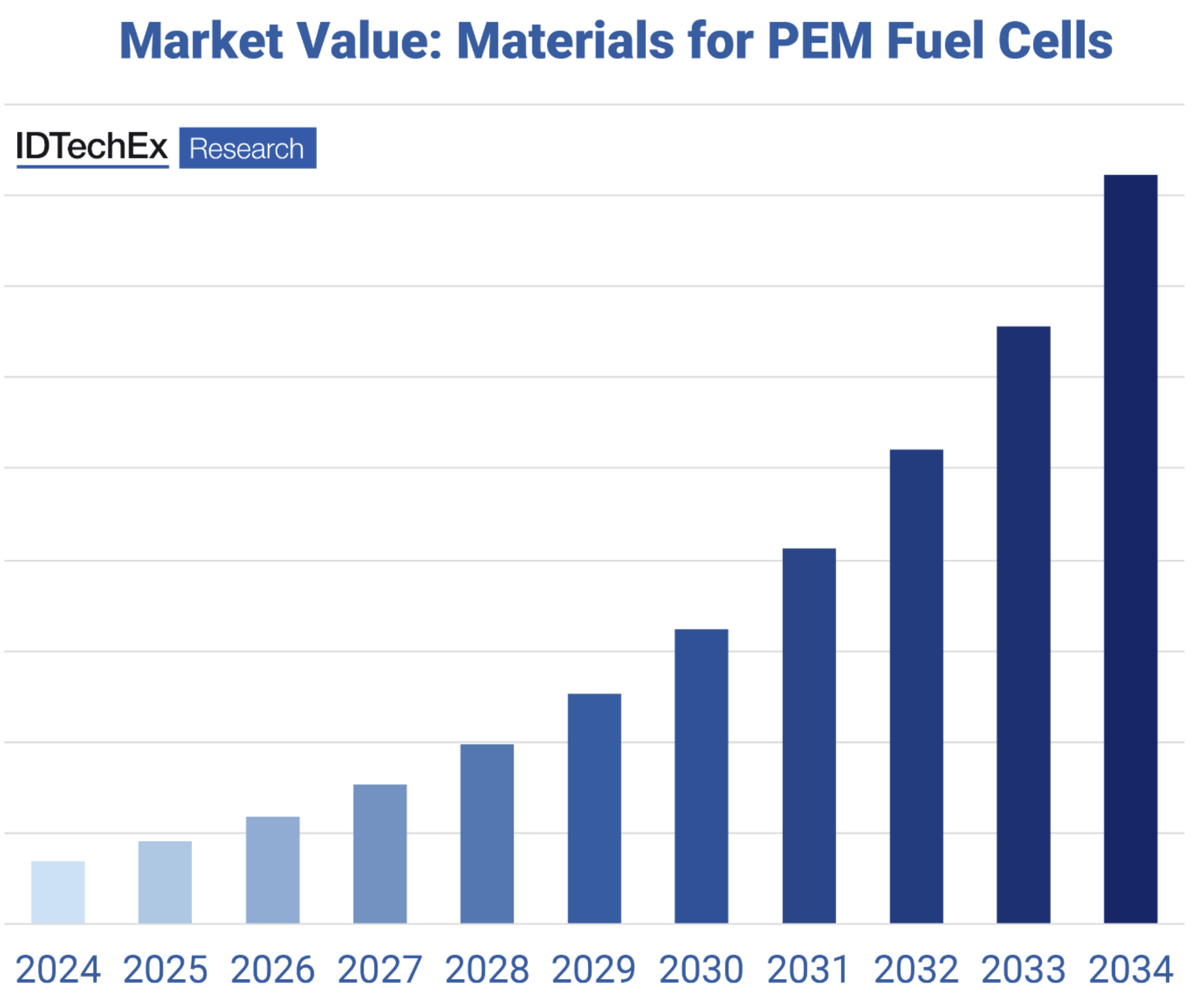
Membrane

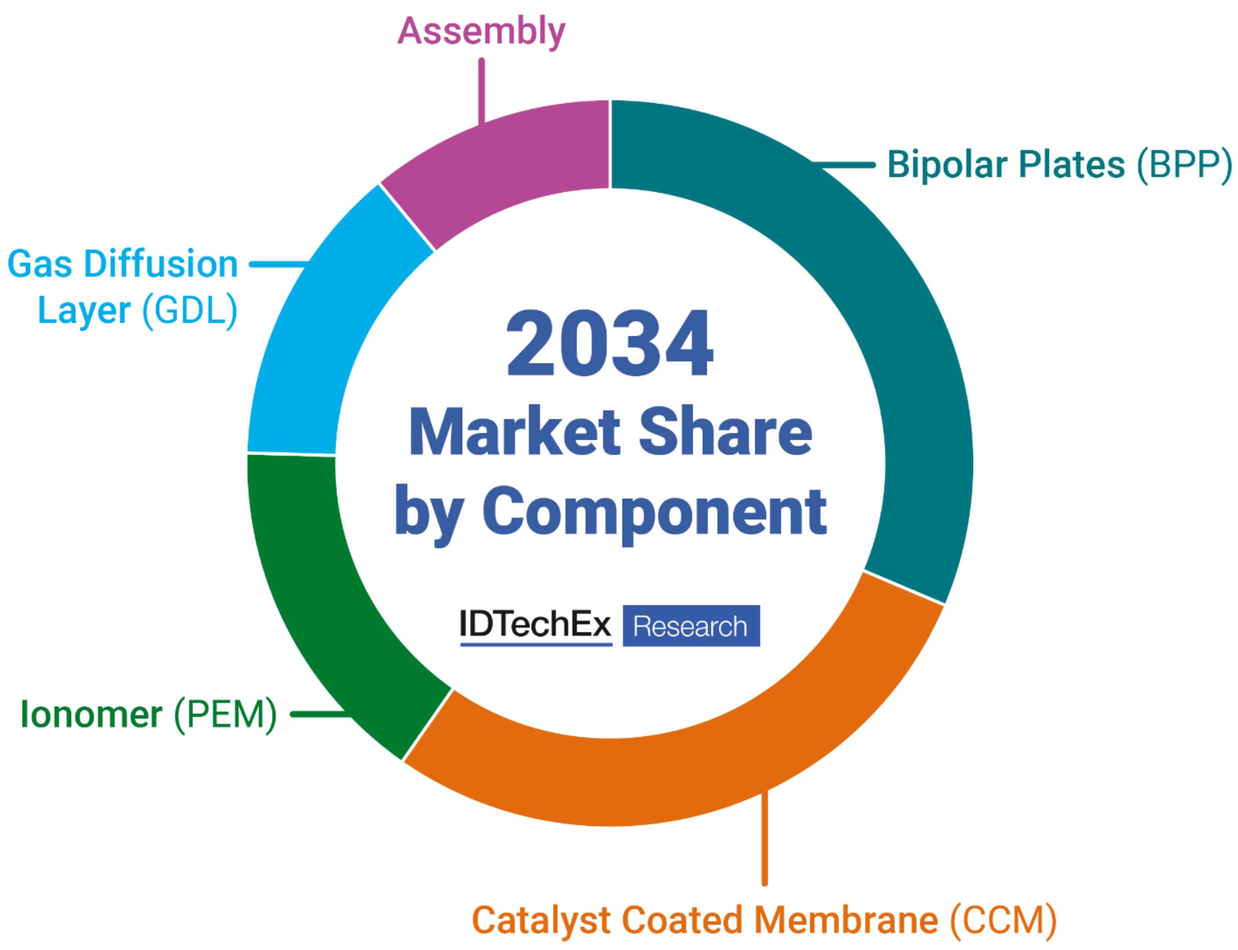
Transports protons from one side of the fuel cell to the other.

Bipolar Plate

Distribute fuel throughout the fuel cell and gather current generated in the cell. Predominantly made from metal or graphitic carbon.

The materials market for PEM fuel cells in transportation applications is set to exceed **US$8 billion** by 2034, but which **components** will account for a significant share of the revenue?





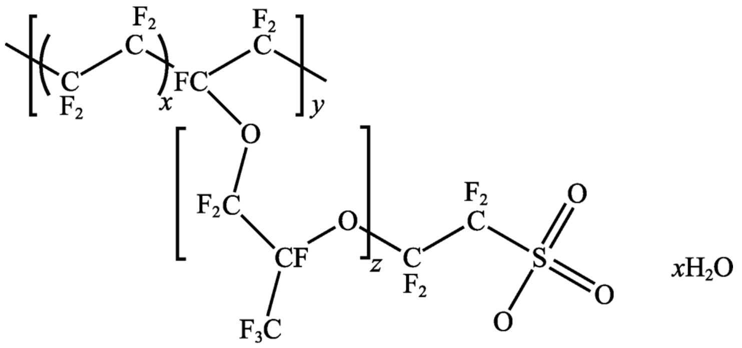
See the full study in IDTechEx's report **"Materials for PEM Fuel Cells 2024-2034: Technologies, Markets, Players"** - www.IDTechEx.com/MPEMFC

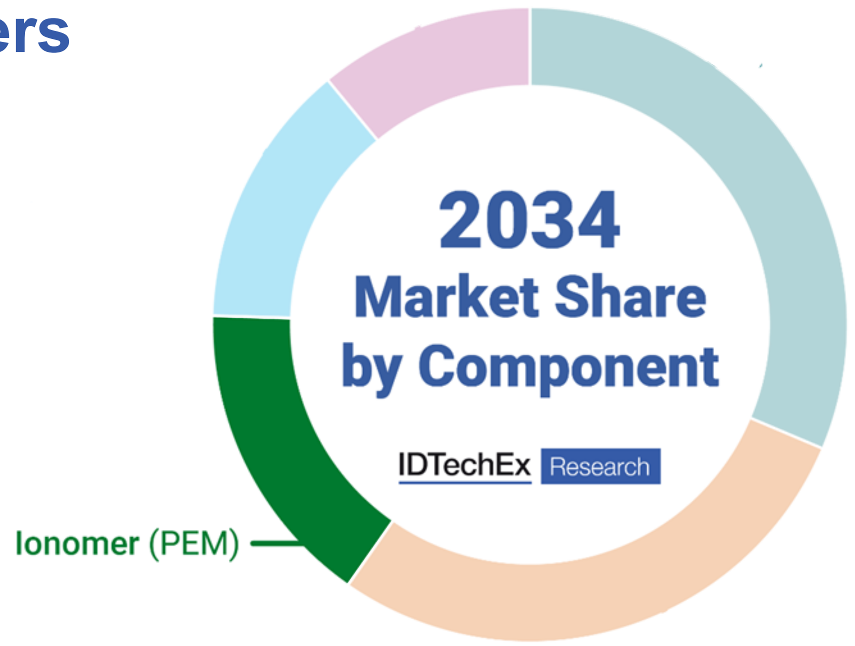
Incumbent Proton Exchange Membranes: Ionomers

The membrane transports protons from one side of the fuel cell to the other, while keeping the fuels separated.

Nafion

- Brand name of a Chemours fluoropolymer-copolymer
- The first ionomer due to its ionic properties





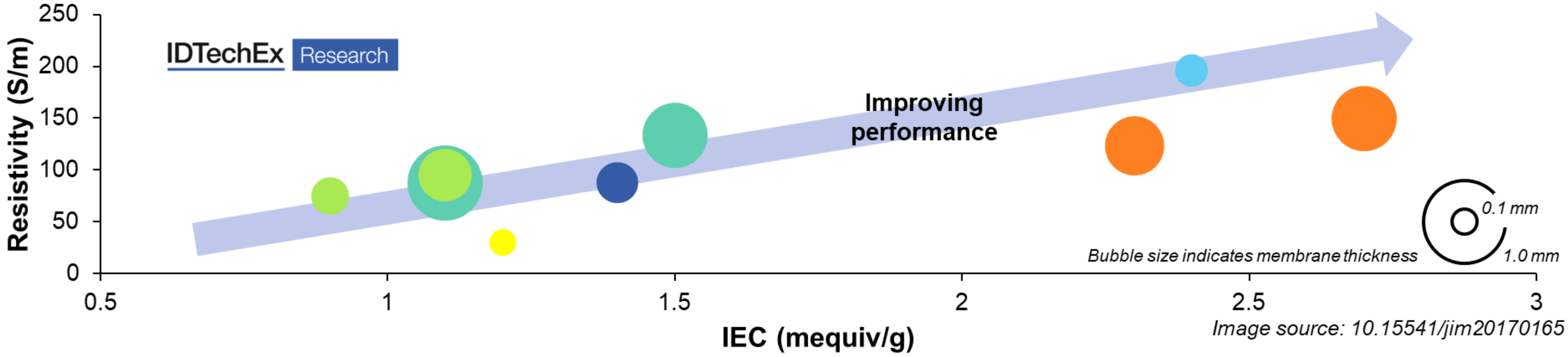


Image source: 10.15541/jim20170165

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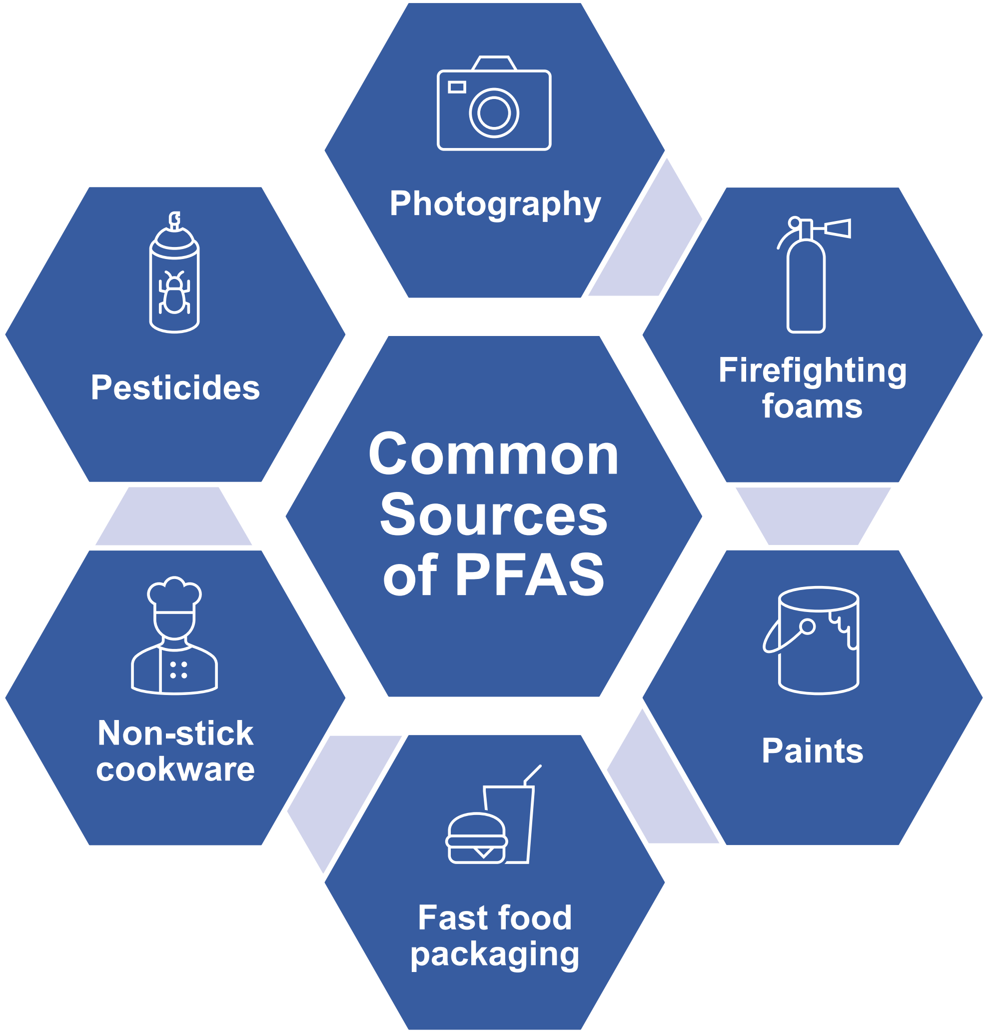
Could PFAS Regulations Affect PEM Fuel Cells & Electrolysers?

Per- and polyfluoroalkyl substances (PFAS) are a family of synthetic chemical compounds:

- Contains at least one fully fluorinated methyl ($-CF_3$) or methylene ($-CF_2-$) carbon atom
- Extremely broad category – including PFOA, PFOS and PTFE.
- Forever chemicals



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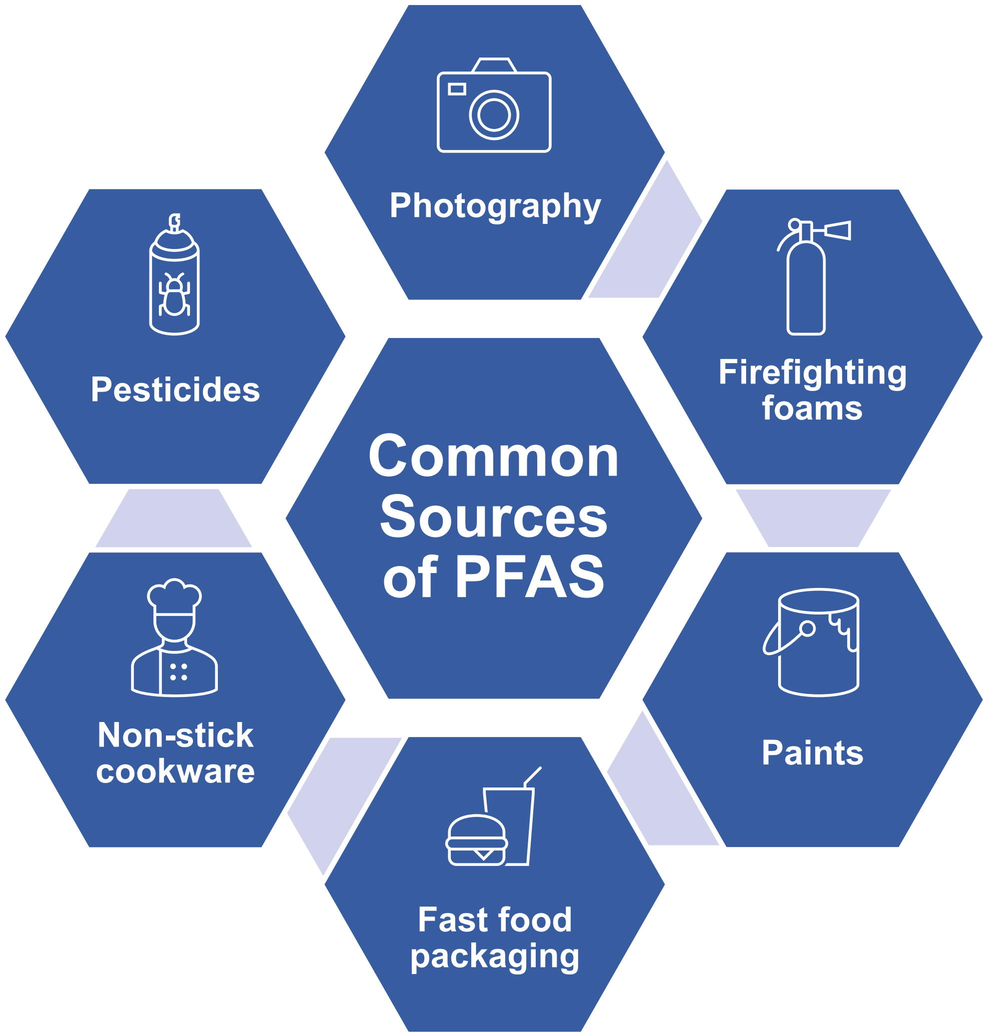

Latest update from the European Chemicals Agency (ECHA):

- Identifying uses not initially named and now assessing regulations. Including sealing applications, technical textiles, printing applications and other medical applications
- Considering alternative restriction options besides full ban or ban with time-limited derogations (initially set 5 years for fuel cells) for applications where may have disproportionate socioeconomic impacts, including; **Batteries, Fuel cells and Electrolyzers**

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IDTechEx Research

Proposed **PFAS regulations** will necessitate the development of **alternative membrane** materials for **PEM fuel cells.** Some of the promising options include hydrocarbons and MOF membranes, but which **material parameters** are key for success?

Chemical Stability

The membrane is subject to oxidizing and reducing environments on either side of the cell and so must be able to exist in harsh, opposing conditions.

Mechanical Strength

A material with a higher strength can be made to be thinner, leading to a higher power density for the fuel cell stack. Reinforcement can be added to the membrane.

Ionic Conductivity

The membrane must transport only protons across the cell. Gas crossover is to be avoided while the fuel cell would be short circuited if the membrane is electrically conductive.

See the full study in IDTechEx's report **"Materials for PEM Fuel Cells 2024-2034: Technologies, Markets, Players"** - www.IDTechEx.com/MPEMFC

Emerging Alternative Membranes

Hydrocarbons

Hydrocarbons have struggled to meet required criteria

Formation of hydroxyl radicals cause **chemical degradation** of the membrane. Solutions such as mediators lead to a reduction in lifetime.

Humidity cycling leads to **mechanical degradation** of the membrane. Hydrocarbons adsorb more water and are stiffer than PFAS.

Solutions are emerging

BASF
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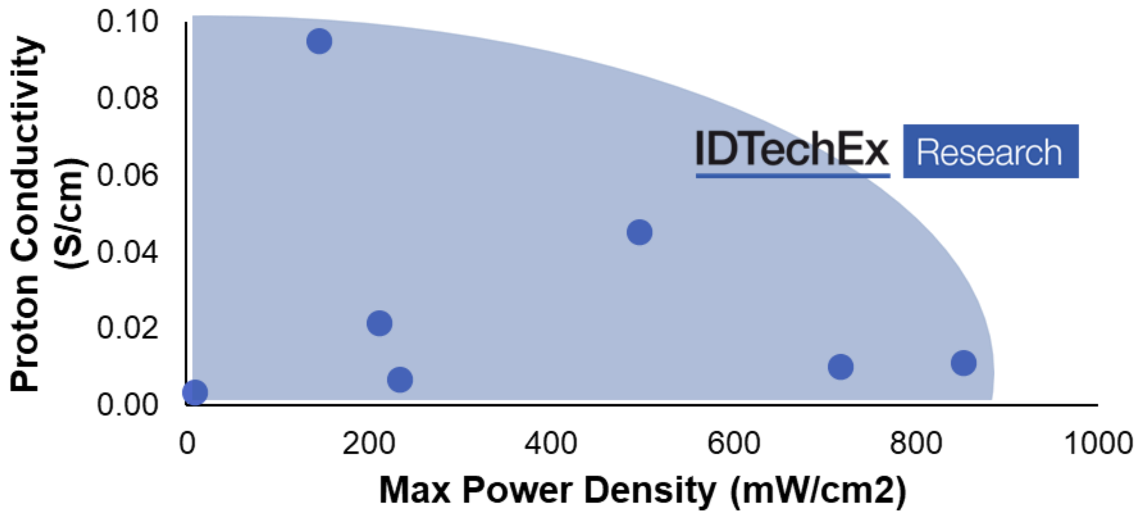
Metal Organic Frameworks (MOFs)

- Tuneable pore size, large surface area and thermal stability
- Typically used in polymer composite membranes
- Still at an early academic stage for development



IDTechEx

Will This Limit the Uptake of PEM Fuel Cells?

Derogations, specifically in the EU, give manufacturers **6.5 years to implement changes** to the design of the fuel cell before restrictions apply. Batteries, fuel cells and electrolyzers considering alternative regulations

Readily available and **ultra-high purity hydrogen** is required for widespread adoption of PEMFCs. For decarbonisation, this should ideally be green H_2.

Competition is fierce from other technologies. For ZEV there is BEV, and growing interest in H2ICE. Stationary applications will be dominated by SOFC and other FCs.

Conclusions

- The **membrane** is one of the **four key components** of a PEM fuel cell, with the material market set to exceed **US$8 billion by the end of the decade**.
- The **incumbent dominant material** is well established.
- Concerns are emerging due to the use of **PFAS** materials and **proposed regulations**.
- Any replacement membrane requires **chemical stability**, **mechanical strength** and **ionic conductivity** – options are emerging.
- **Other major concerns** for the success of PEMFCs include the **need for ultra pure hydrogen** and **strong competition** in many fields.

Materials for PEM Fuel Cells 2024-2034

www.IDTechEx.com/MPEMFC

Sample pages are available for all IDTechEx reports

Presenter – Maia Benstead

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Recent innovations and future advances of alternatives to PFAS in lithium-ion batteries (and other green energy technologies)

Amanda Rensmo

PhD student, Stockholm University

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036756.

Acknowledgements

Eleni Savvidou

Ian Cousins

Jon Benskin

Steffen Schellenberger

Xianfeng Hu

Marcel Weil

and others...

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Cite this: *Environ. Sci.: Processes Impacts*, 2023, **25**, 1015

Lithium-ion battery recycling: a source of per- and polyfluoroalkyl substances (PFAS) to the environment?

Amanda Rensmo, *ab Eleni K. Savvidou, b Ian T. Cousins, b Xianfeng Hu, c Steffen Schellenberger †a and Jonathan P. Benskin †b

Recycling of lithium-ion batteries (LIBs) is a rapidly growing industry, which is vital to address the increasing demand for metals, and to achieve a sustainable circular economy. Relatively little information is known about the environmental risks posed by LIB recycling, in particular with regards to the emission of persistent (in)organic fluorinated chemicals. Here we present an overview on the use of fluorinated substances – in particular per- and polyfluoroalkyl substances (PFAS) – in state-of-the-art LIBs, along with recycling conditions which may lead to their formation and/or release to the environment. Both organic and inorganic fluorinated substances are widely reported in LIB components, including the electrodes and binder, electrolyte (and additives), and separator. Among the most common substances are $LiPF_6$ (an electrolyte salt), and the polymeric PFAS polyvinylidene fluoride (used as an electrode binder and a separator). Currently the most common LIB recycling process involves pyrometallurgy, which operates at high temperatures (up to 1600 °C), sufficient for PFAS mineralization. However, hydrome temperat persisten in bench emission materials condition

Received 8th December 2022
Accepted 23rd April 2023

DOI: 10.1039/d2em00511e

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Perspective

PFAS-Free Energy Storage: Investigating Alternatives for Lithium-Ion Batteries

Eleni K. Savvidou,* Amanda Rensmo, Jonathan P. Benskin, Steffen Schellenberger, Xianfeng Hu, Marcel Weil, and Ian T. Cousins*

Cite This: *Environ. Sci. Technol.* 2024, 58, 21908–21917

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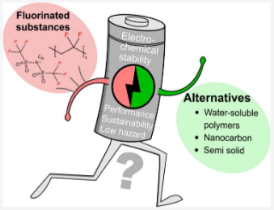
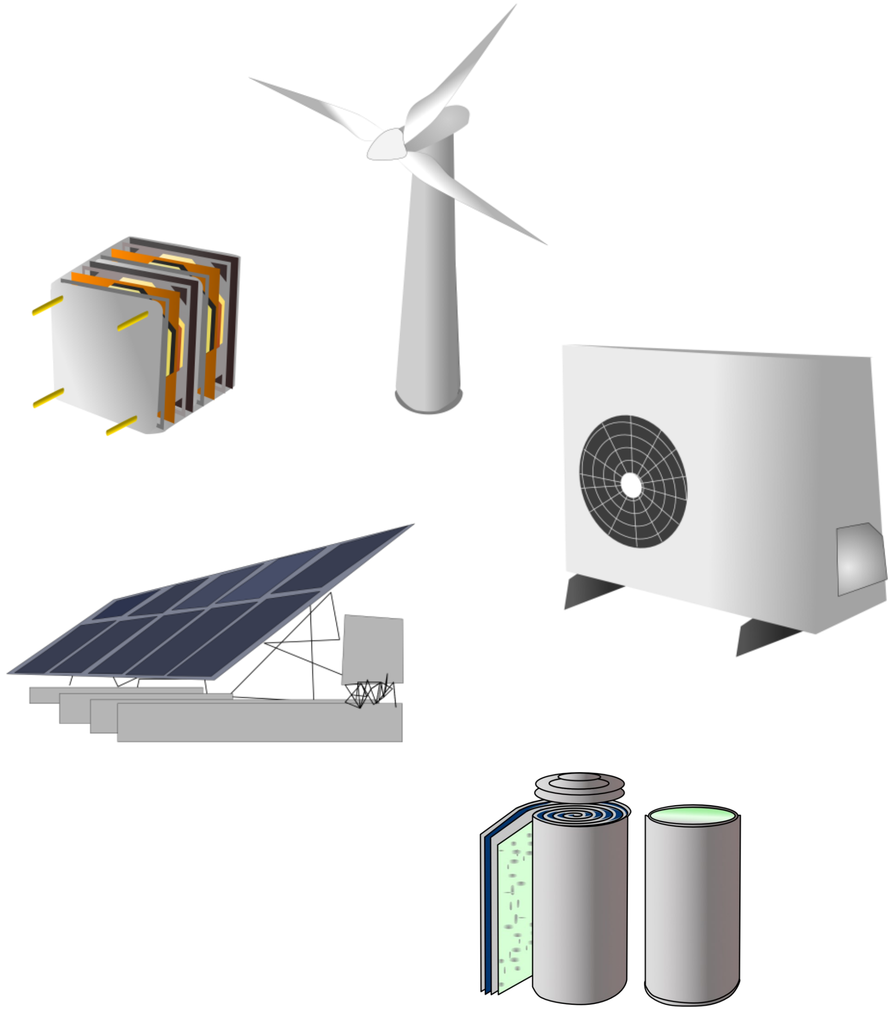


ABSTRACT: The class-wide restriction proposal on perfluoroalkyl and polyfluoroalkyl substances (PFAS) in the European Union is expected to affect a wide range of commercial sectors, including the lithium-ion battery (LIB) industry, where both polymeric and low molecular weight PFAS are used. The PFAS restriction dossiers currently state that there is weak evidence for viable alternatives to the use of PFAS in LIBs. In this Perspective, we summarize both the peer-reviewed literature and expert opinions from academia and industry to verify the legitimacy of the claims surrounding the lack of alternatives. Our assessment is limited to the electrodes and electrolyte, which account for the most critical uses of PFAS in LIB cells. Companies that already offer or are developing PFAS-free electrode and electrolyte materials were identified. There are also indications that PFAS-free electrolytes are in development by at least one other company, but there is no information regarding the alternative chemistries being proposed. Our review suggests that it is technically feasible to make PFAS-free batteries for battery applications, but PFAS-free solutions are not currently well-established on the market. Successful substitution of PFAS will require an appropriate balance among battery performance, the environmental effects associated with hazardous materials and chemicals, and economic considerations.

KEYWORDS: *fluoropolymers, PVDF, renewable energy, green energy transition, cathode, binder, electrolyte salt, electrolyte additives*

Are PFAS essential in green energy technologies (GETs)? Should *we* allow the use of PFAS in GETs?

- Not a yes/no question
  - Look closer (components)
  - Look broader (sub-uses)
- Today, there are commercially available alternatives to PFAS (technology and/or material)
- Full alternatives assessments are necessary to avoid regrettable substitution



Background: Fluoropolymers are included in the definition of PFAS

"PFASs are defined as fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), i.e. with a few noted exceptions, any chemical with at least a perfluorinated methyl group (–CF3) or a perfluorinated methylene group (–CF2–) is a PFAS."

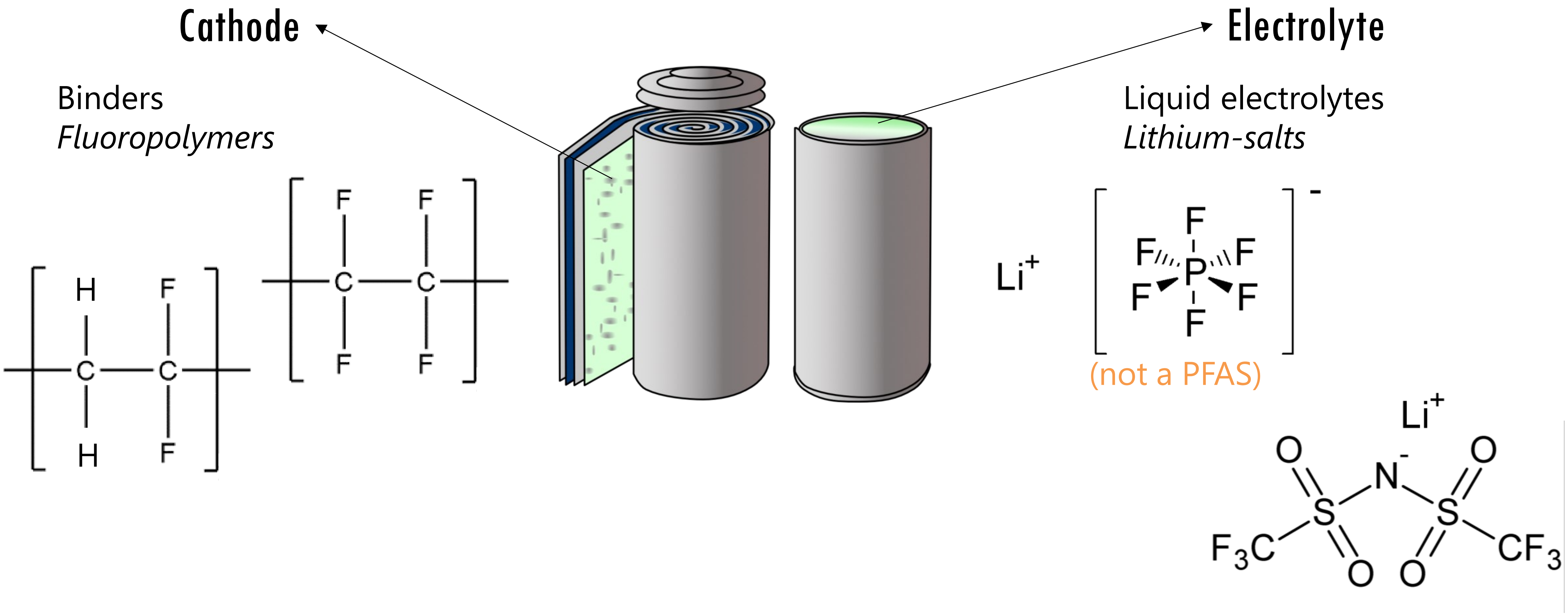
OECD

ECHA
EUROPEAN CHEMICALS AGENCY

"All PFASs are considered to be very persistent, either on the basis of their own very persistent properties or the very persistent properties of their terminal degradation product (arrowhead) Additional hazardous properties depend on the specific structure of a PFAS."

OECD (2021)
ECHA (2023)

Case 1: PFAS are used in lithium-ion batteries as binder and electrolyte, e.g. PVDF and TFSI



Rensmo et al (2023)
Savvidou et al. (2024)

“The inclusion of **fluorine-based compounds** in the electrolyte chemistry is, to date, ubiquitous as a pathway to promote the targeted formation of lithium fluoride, known to be a favourable SEI component in lithium batteries.“

“By increasing the **perfluoroalkyl chains** in the sulfonimide anions, efficient stabilization of cathode-electrolyte interface could be also achieved.[189]”

189. Tong B et al. (2023) Design of a Teflon-like Anion for Unprecedently Enhanced Lithium Metal Polymer Batteries *Adv. Energy Mater.* **13** 2204085

“Presently, the dry PE-based SSBs, consisting of a thin membrane of **LiTFSI**/PEO, metallic lithium (Li°) anode, and LiFePO4 cathode, have been employed as power source for EVs (e.g. Bluecars®, Bluebuses®) and grid storage (e.g. Bluestorage®).”

“…with increasing concerns on the use of polyfluoroalkyl substances (PFASs; being harmful to human and animals), excluding long **perfluorinated chains from polymers and salts** would be important for attaining sustainable technology with PE-based SSBs.”

JPhys Energy

ROADMAP • OPEN ACCESS

2024 roadmap for sustainable batteries

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Published 8 October 2024 • © 2024 The Author(s). Published by IOP Publishing Ltd

Journal of Physics: Energy, Volume 6, Number 4

Citation Magda Titirici *et al* 2024 *J. Phys. Energy* **6** 041502

DOI 10.1088/2515-7655/ad6bc0

… and also in “future” battery technologies

Case 1: There are various alternatives on the market to PVDF and TFSI

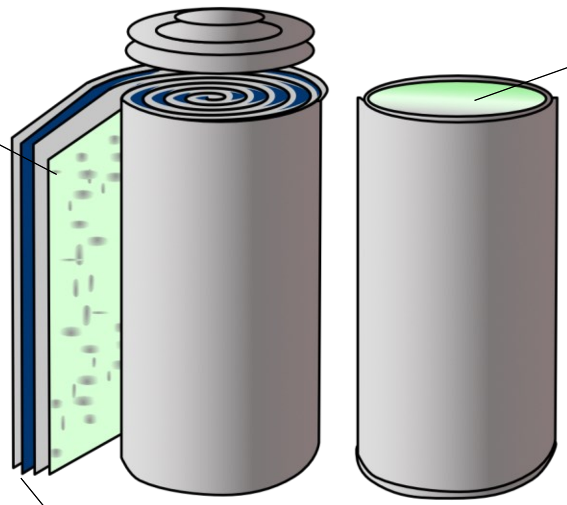
*lists not exhaustive

Cathode

Water-soluble binders
Biobased polymers

Solvent-free binders
Nanocarbon

Binder-free technologies



Electrolyte

Liquid electrolytes
E.g. borates

Polymer electrolytes
Poly(ethylene oxide)

Solid/Metal batteries
PFAS-free ionic liquids
See more in Liu et al. (2025)

Anode

Styrene-Butadiene Rubber (SBR)
Carboxymethylcellulose (CMC)
Polyacrylic acid (PAA)

Savvidou et al. (2024)

Case 2: The chemical industry, parts suppliers and wind energy sceptics claim that PFAS is used in wind energy

"In particular, fluoropolymers are key materials for the majority of the strategic technologies assessed including Li-ion batteries, fuel cells, wind turbines, solar photovoltaics"

"In the field of wind turbines, fluoropolymers are used as coatings on the towers and blades of wind power generators…"

"…ticking PFAS bomb under the wind turbines that stand out at sea…" (translated)

"County Opposes Lake Erie Wind Turbines:
/…/Some of the resolution noted included:/…/
- Release of microplastics and toxic chemicals, such as BPA and PFAS, from wind turbine materials"

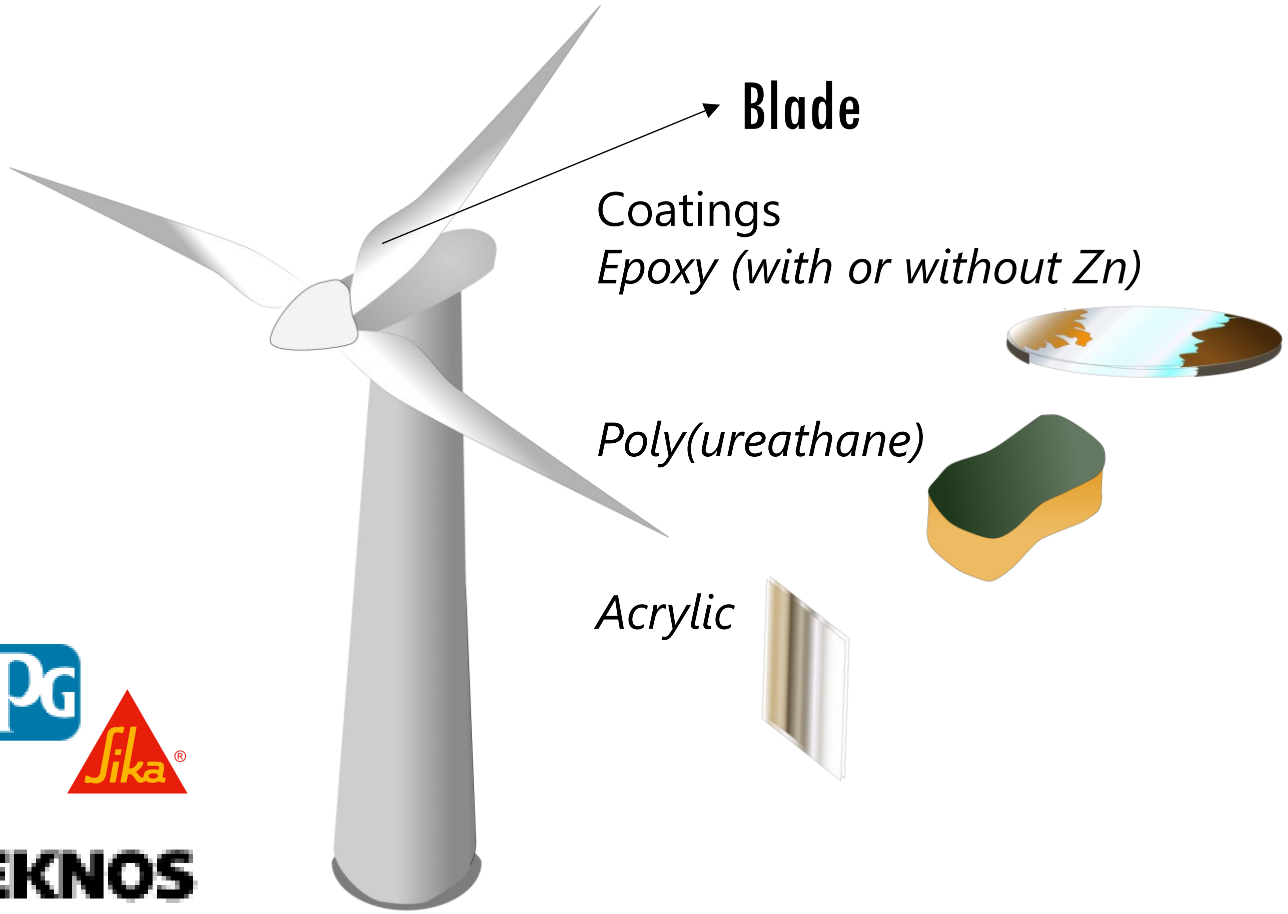
ECHA submissions: FPG Fluoropolymers Product Group (ref_6148), 3P Performance Plastics Products (ref_6275); Media: Ingeniøren (Danish), The Post-Journal

Case 2: Commercial wind turbines do not contain PFAS in the main components such as the blade

"The wind industry is already using PFAS-free coatings for the rotor blades. And it continuously assesses whether other components and materials may contain PFAS and, if so, whether PFAS-free alternatives are available."

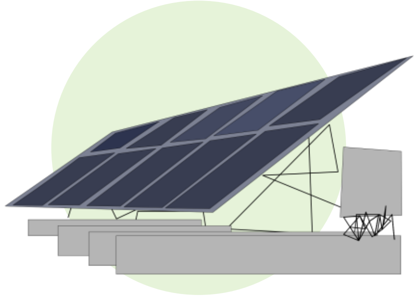
Wind EUROPE

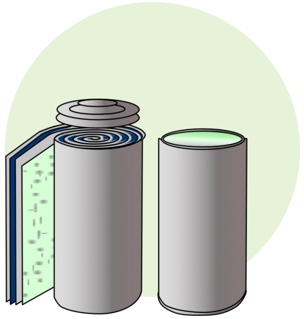
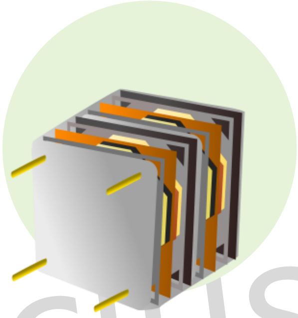
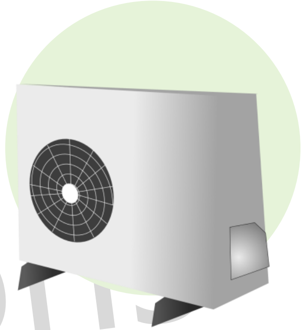
SHERWIN WILLIAMS. PPG AkzoNobel BELZONA Repair • Protect • Improve Sika HEMPEL TEKNOS



B. Kjærside Storm (2013)
A. Dashtkar et al. (2019)

What about major GETs – do they use PFAS or not? If so, are there alternatives on the market?



Intermediate conclusions

Solar panels (Si)	Wind turbines	Batteries (Li-NMC)	Fuel cells (PEM)	Heat pumps
PFAS in supporting components	No PFAS in main components	PFAS in main component(s)	PFAS in main component	PFAS in main component
Market alternatives available	"Alternatives" implemented	Alternative sub-uses without PFAS in main component(s)	Alternative sub-uses without PFAS in main component	Alternatives available, historically used

See more in Glüge et al. (2024)

Are PFAS essential in green energy technologies (GETs)? Should *we* allow the use of PFAS in GETs?

- All five major GETs have PFAS-free alternatives (technology and/or material) with various TRL
- Some functions are shared among several GETs
- My work: Look closer and broader
  - use of PFAS in both main and supporting components of GETs
  - uses of PFAS for different sub-uses of GETs

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"There are a number of scientific approaches we can take to make a safer and more sustainable environment, whilst still improving the usability of energy storage [including] remov[ing] chemicals that can potentially produce such toxic materials as PFAS during recycling"

J Power Sources. 2020 Oct 15; 473: 228574.
Published online 2020 Jul 27.
doi: 10.1016/j.jpowsour.2020.228574

Beyond the Nobel recognition – To a cleaner sustainable future

M. Stanley Whittingham

ZeroPM

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036756.

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