Overview of existing PFAS treatment technologies concerning Soil, Water and Air

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Overview of existing PFAS treatment technologies concerning Soil, Water and Air

Panoplie des technologies des traitements de dépollution des sols, eaux et de l'air existants concernant les PFAS

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CEO-President of HPC INTERNATIONAL / France, Germany, Switzerland, Hungary, Balkan, etc.

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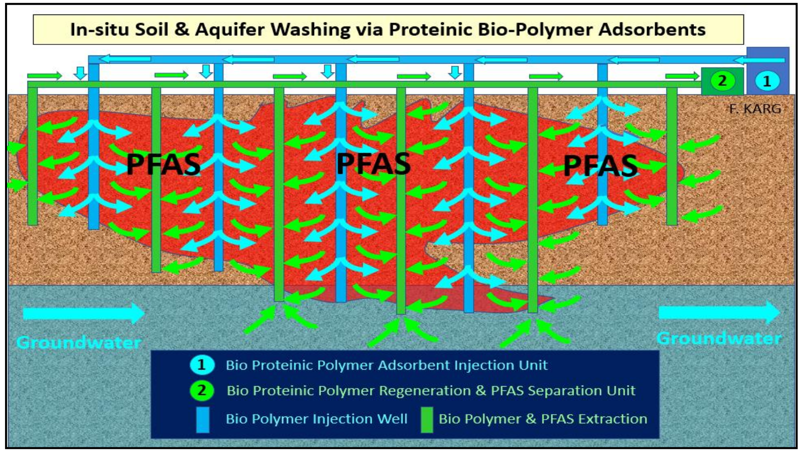

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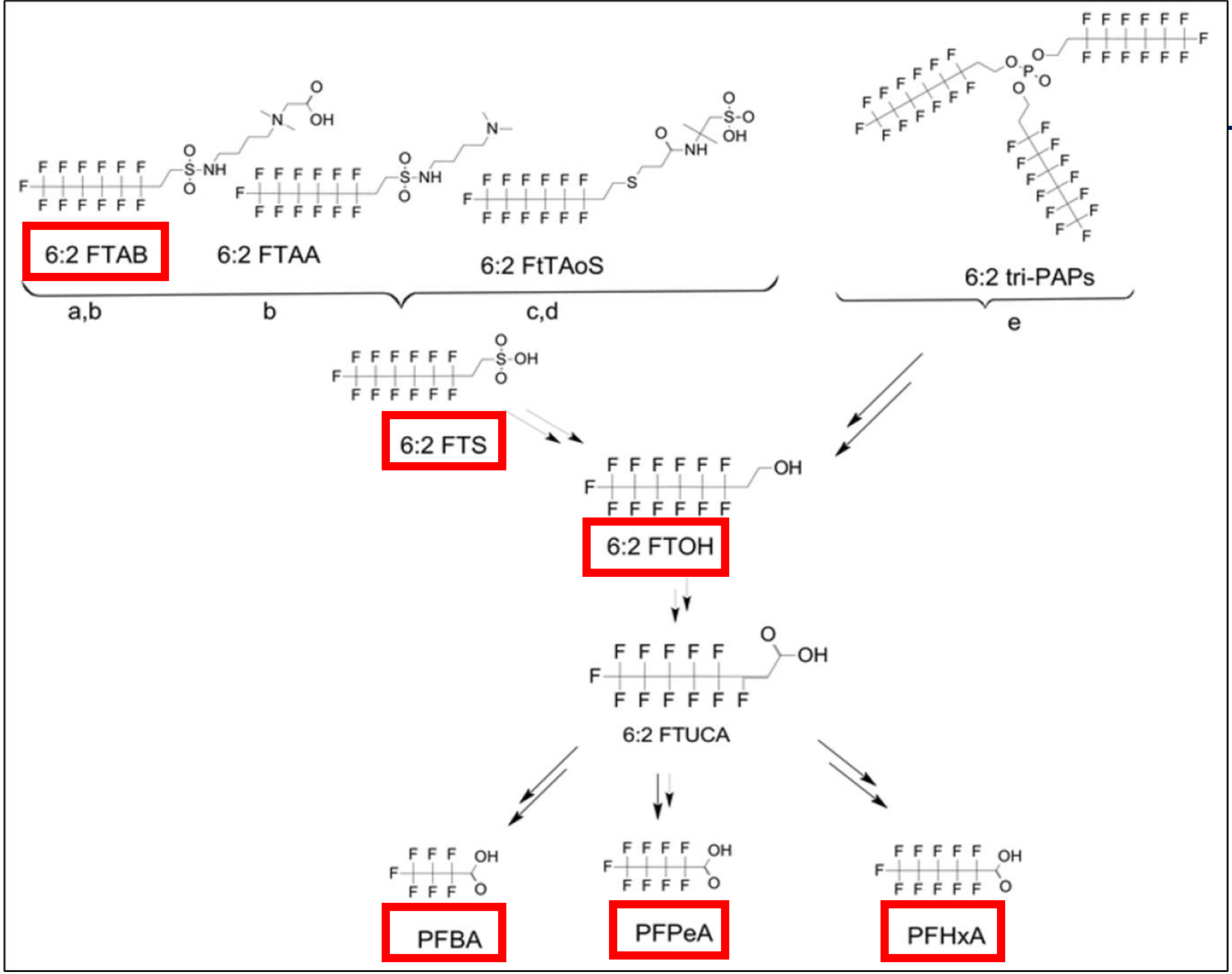
In minimum 33 Categories

1. Perfluoroalkane-sulfonic-acids (PFASs),
2. Perfluoroalkane-sulfonats (salts),
3. Perfluoroalkane-sulfinic-acid/sulfonates,
4. Perfluoro-cycloalkane-sulfonic-acids & derivats,
5. Perfluoroalkane-sulfonamids (FASAs),
6. Perfluoroalkane-sulfonamide & quaternary ammonium salts,
7. Acrylate de perfluoroalkane-sulfonamide (MeFASACs),
8. Perfluoroalkane-sulfonamide methylacrylates,
9. Perfluoroalkane-sulfonamide phosphates,
10. Perfluoroalkane-sulfonyl halogenureas,
11. Different polyfluoroalkyl-sulfur compounds,
12. Perfluoroalkyl-carboxyl-acids (PFCA),
13. Perfluoroalkyl-carboxyl-acids,
14. Perfluoroalkyl-alcohols/cetones,
15. Halogenurea perfluoroalkyl-carboxylic acids,
16. Perfluoroalkyl-halogenureas,
17. Perfluoroalkyl-ethers,
18. Perfluoroalkyl-amines,
19. Perfluoroalkyl-amino-acides/salts/esters,
20. Perfluoroalkyl-phosphates,
21. Perfluoroalkyl-acrylate,
22. Perfluoroalkyl-methacrylates,
23. Other Perfluoroalkyl-carboxylic esters,
24. Perfluoroalkyl-heterocyclic Compounds,
25. Perfluoroalkyl-silanes,
26. Fluorotelomer-alcools,
27. Fluorotelomer halogenides,
28. Fluorotelomer sulfonates, sulfonyl chlorides and sulfonamides,
29. Fluorotelomer Acrylates,
30. Fluorotelomer Methylacrylates
31. Other Fluorotelomer Acrylates
32. Fluorotelomer phosphates,
33. Other fluorotelomers.

In total > 9 000 – 12 000 PFAS are existing !



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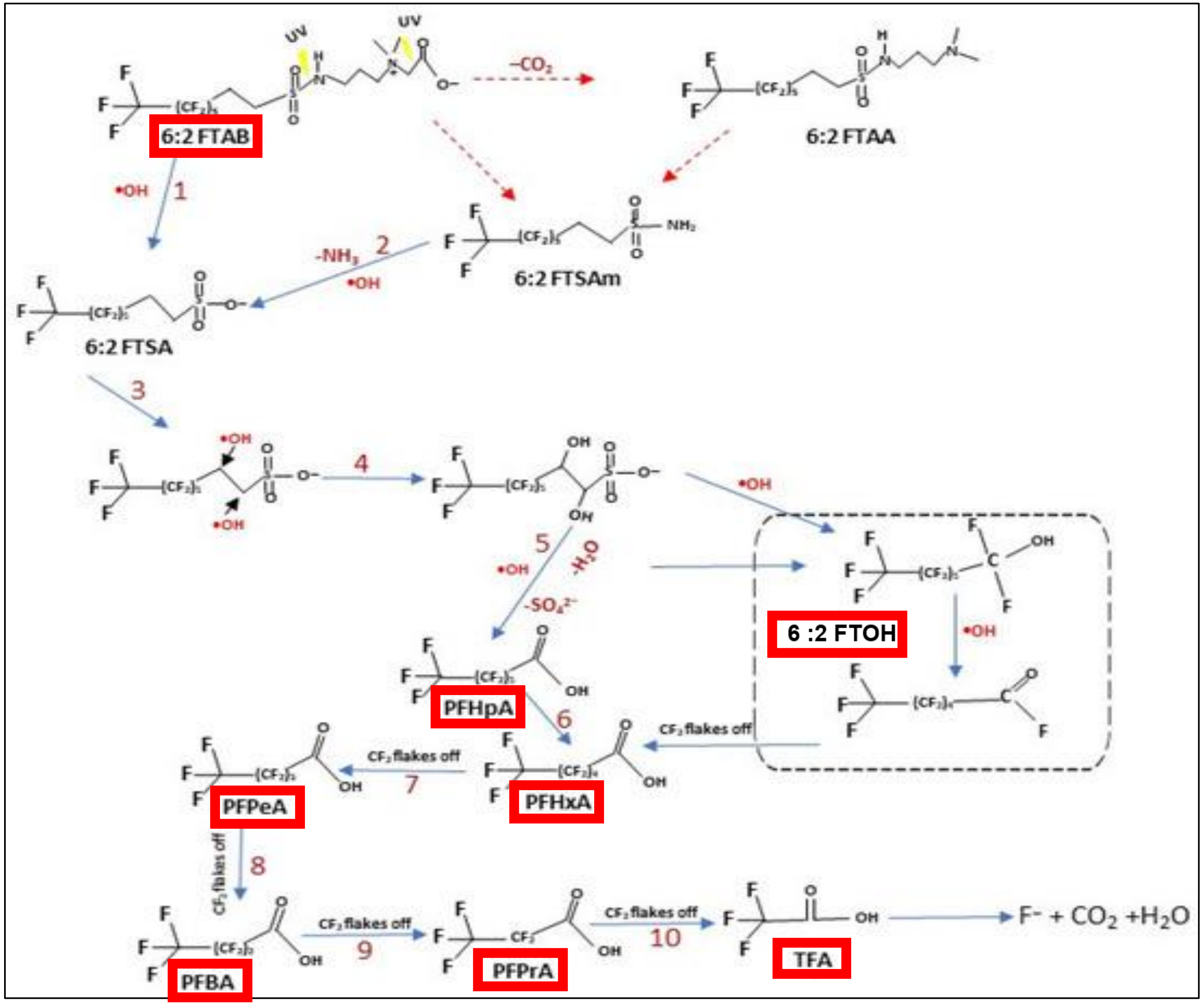
6 :2 FTAB: Degradation

via 6 :2 FTS and 6 :2 FTOH to per-fluorinated PFBA, PFPeA & PFHxA

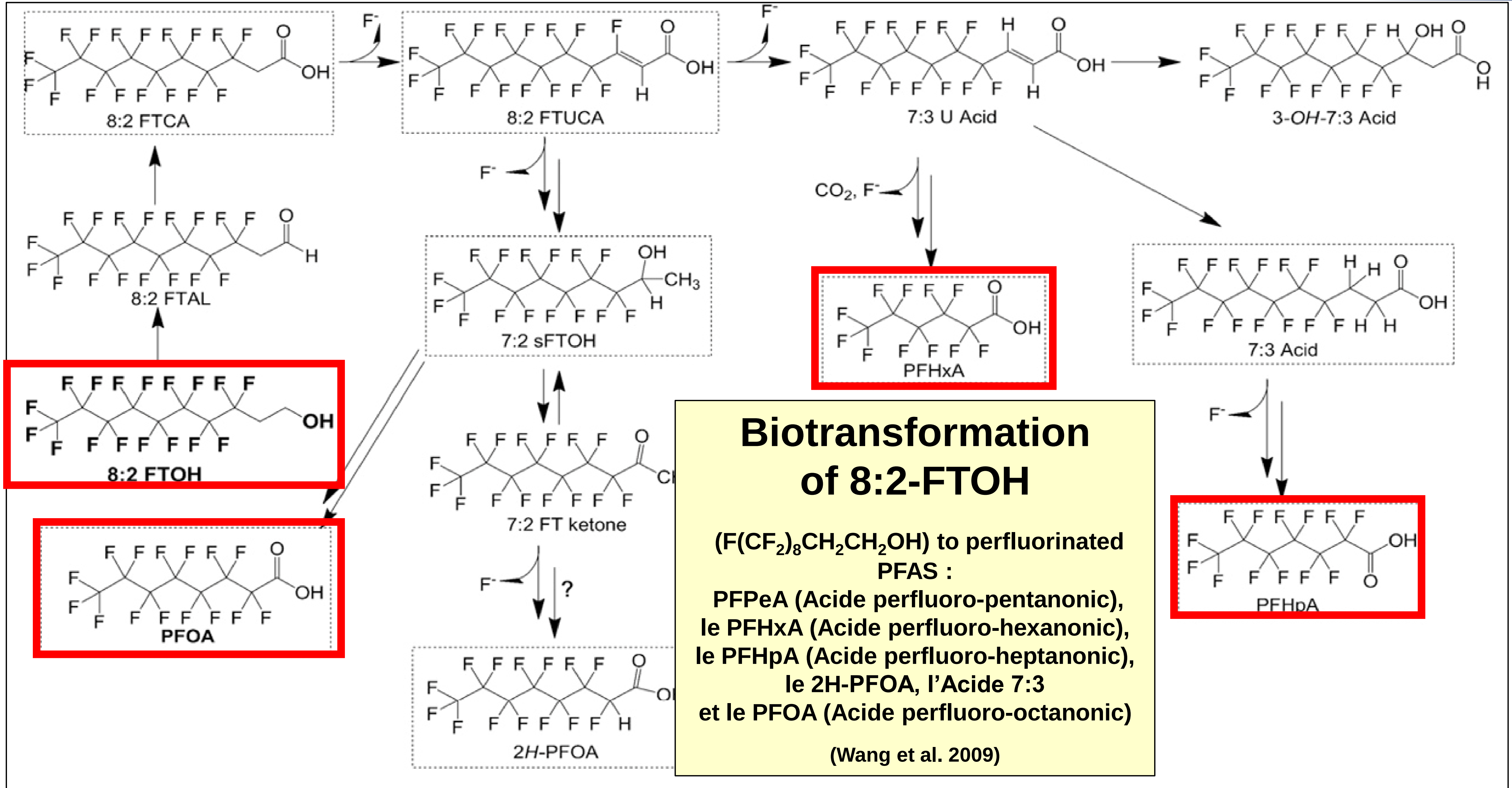
(LaFond et al. 2023, D.M.J. Shaw et al. 2019 ,Ying Shi, 2018 and V. Mendeza et. al. 2022)



6 :2 FTAB Photolysis:

via 6:2 FTOH to PFHxA, PFPeA, PFBA, PFPrA & TFA

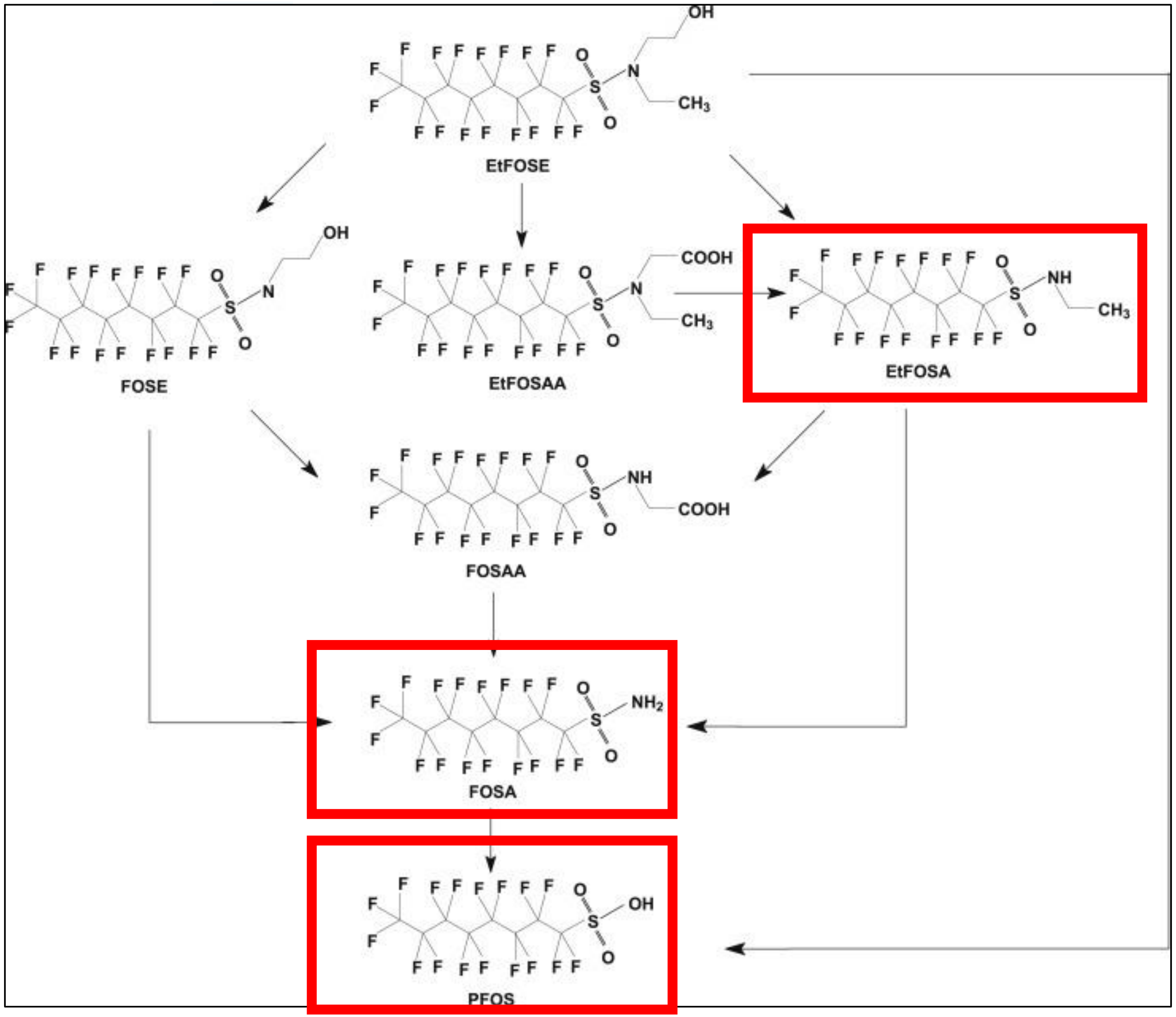
(Naveed, A. et al 2024)



Biotransformation of 8:2-FTOH

($F(CF_2)_8CH_2CH_2OH$) to perfluorinated PFAS :
PFPeA (Acide perfluoro-pentanonic),
le PFHxA (Acide perfluoro-hexanonic),
le PFHpA (Acide perfluoro-heptanonic),
le 2H-PFOA, l'Acide 7:3
et le PFOA (Acide perfluoro-octanonic)

(Wang et al. 2009)



PFAS: Environnemental Chemistry

Bio-transformation

of EtFOSE, EtFOSA &

FOSA to PFOS

S. Chen et al. 2021

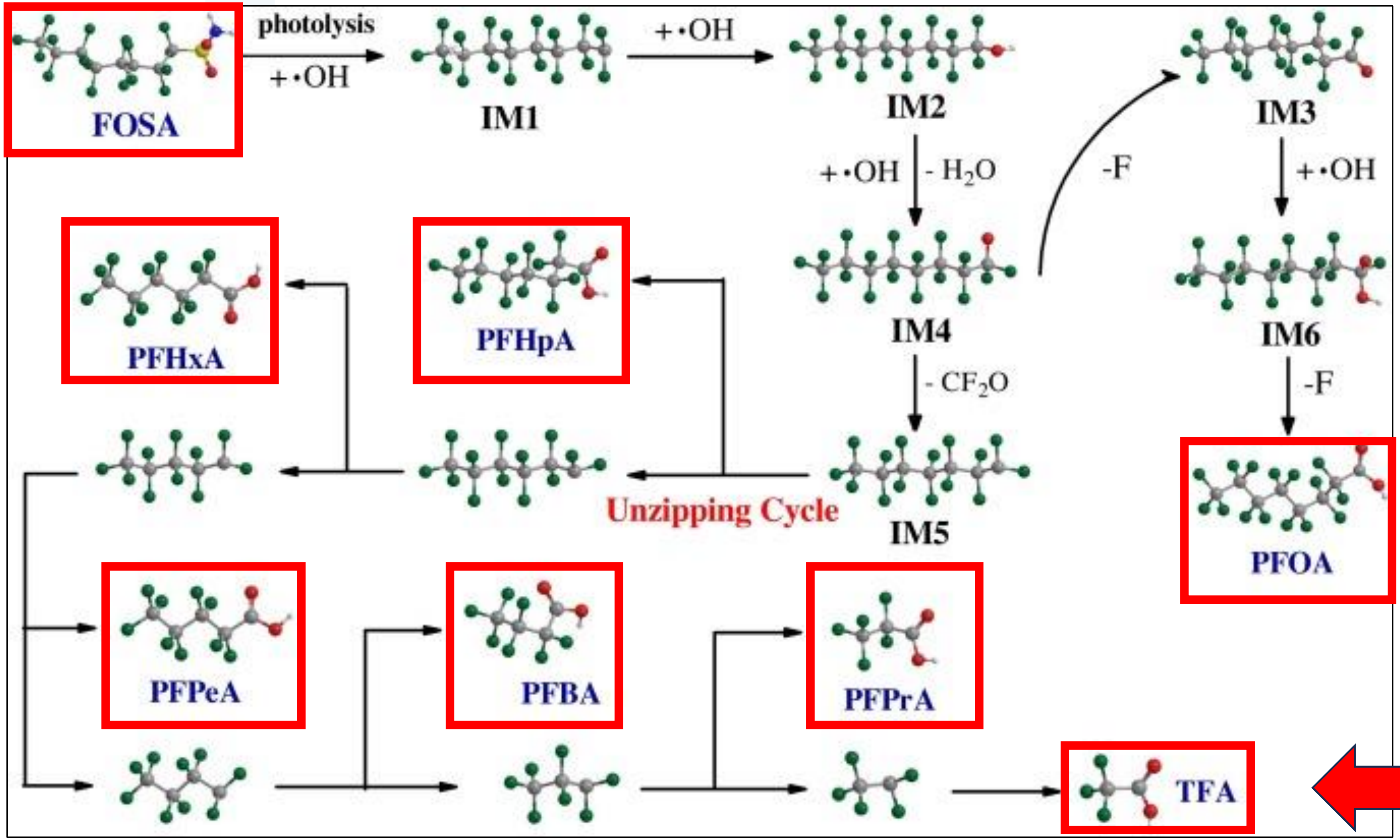
Scotchban FC 807

= 100 % EtFOSA

Impregnation of

Papers & Textiles

PFOS

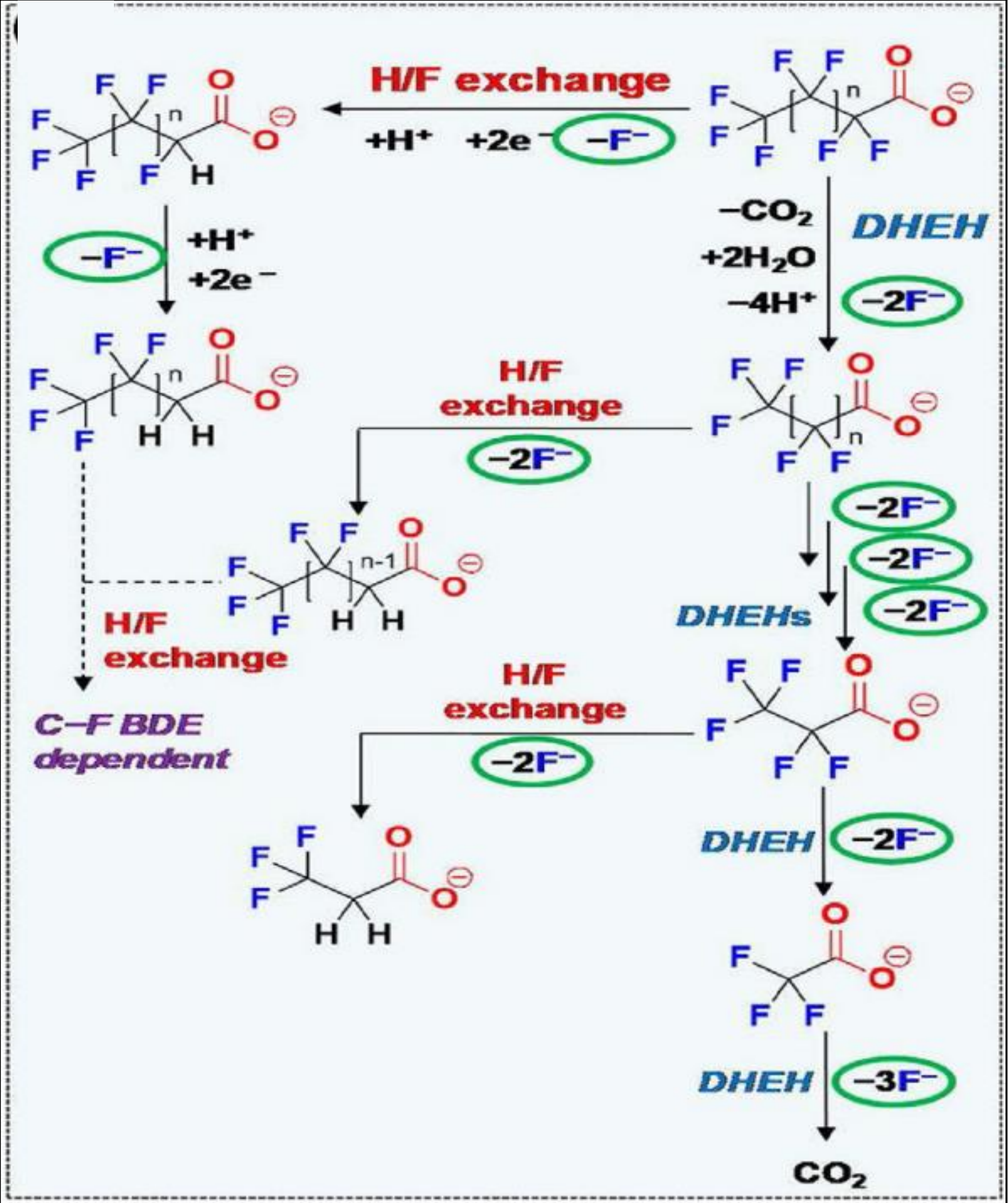


PFAS: Environmental Chemistry

Photolysis of FOSA to PFOA, PFNA, PFHpA, PFHxA, PFPeA, PFBA, PFPrA, TFA

Y. Wang 2020

TFA



PFAS: Environmental Chemistry

Photochemical defluorination of PFBA to TFA

Bentel et al. 2019 & Masruck, A. et al. 2020)

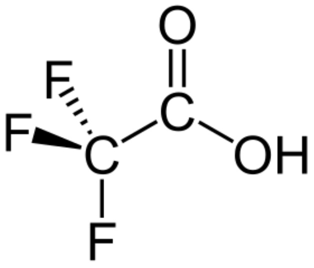
Ultrashort PFAS:

- TFA: Trifluoro acetic acid: CAS: 76-05-1
- TFMS: Trifluoro methane sulfonic acid: CAS: 1493-13-6
- PFES: Penta(per)fluoro ethane sulfonic acid: 354-88-1
- PFPrA: Perfluoro propanonic acid: CAS: 422-64-0
- PFPrS: Perfluoro propane sulfonic acid: CAS: 423-41-6

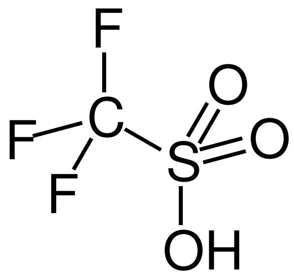
TFA

PFAS: Environmental Chemistry

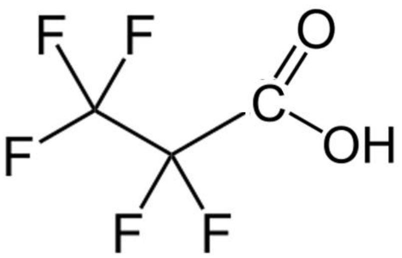
Other (semi) volatile PFAS



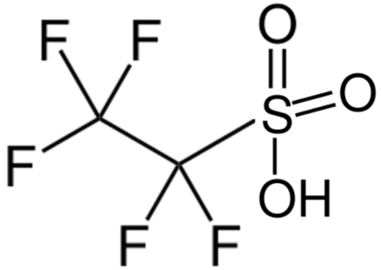
TFA



TFMS



PFPrA



PFES

- **FTOH: Fluorotelomer-alcohols (**4:2-FTOH, 4:3-FTOH, **6:2-FTOH**, 6:3-FTOH, **8:2-FTOH**, 10:2-FTOH, etc.),
- **FASE: Per-fluoroalkane-sulfamide-ethanols** (par ex. N-**MeFOSE, N-EtFOSE**),
- **FTI: Fluorotelomer-iodits** (par ex.. **6:2-FTI**, 8:2-FTI, 10:2-FTI),
- **FTAC: Fluorotelomere-acrylates** (par ex. 4:2-FTAC, **6:2-FTAC, 8:2-FTAC**, 10:2-FTAC),
- **FTMACS: 6:2-Fluorotelomer-methylacrylats** (par ex. 4:2-FTMAC, **6:2-FTMAC**, 8:2-FTMAC, 10:2-FTMAC),
- **PFADiI: Perfluoroalkyl-di-iodits** (par ex. PFBuDiI, **PFHxDiI**, PFODiI),
- **TFMB: Trifluormethylbenzenes** (z.B. BTFMBB: 1-Brom-3,5-bis(trifluoro-methyl)benzol).

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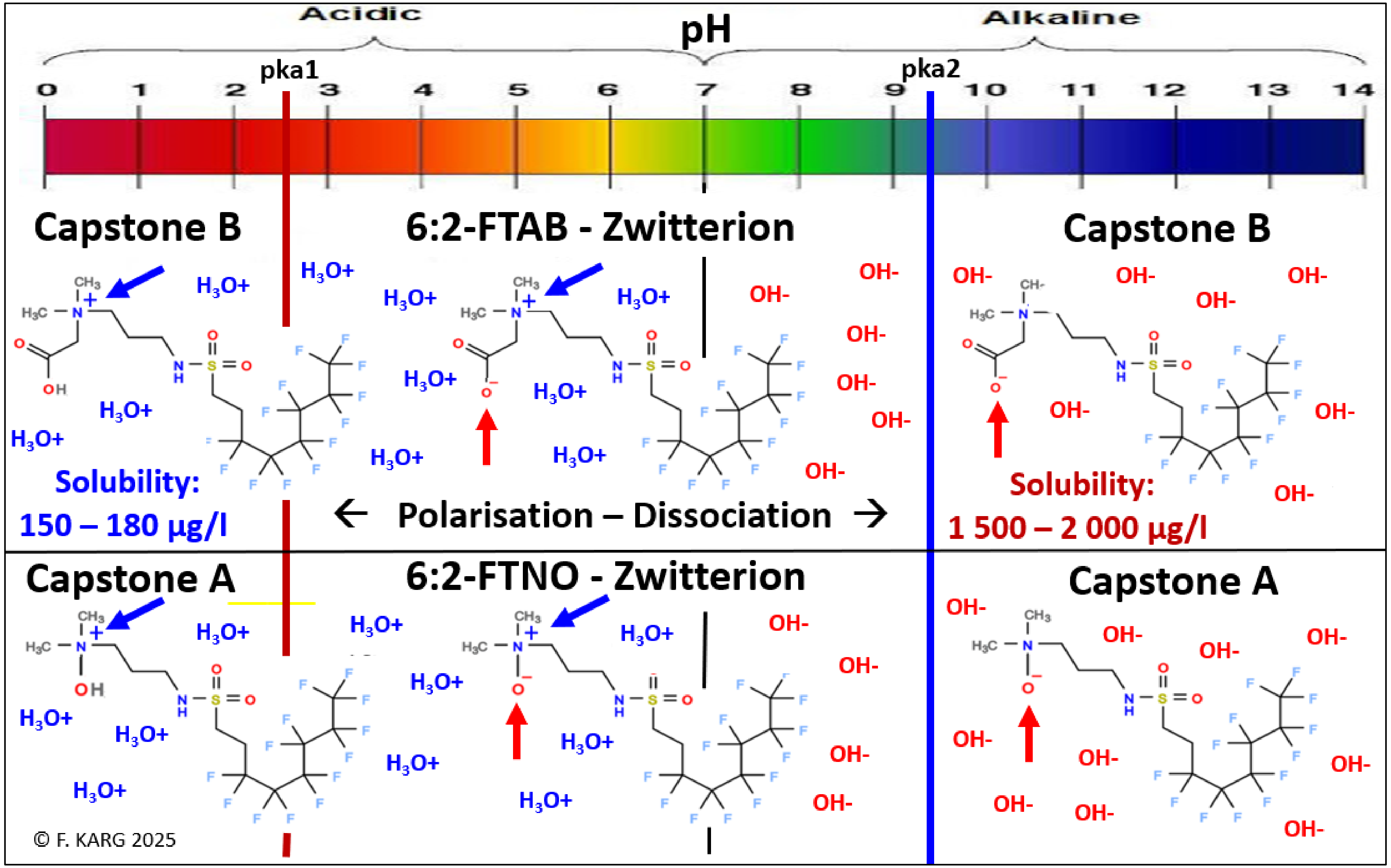

Environmental Chemistry according pH of Capstone A & B

TOF: Total Organo Fluorine

= PFAS Monomers & Polymers + other organo-fluorine Compounds; Pesticides, Pharmaceuticals, etc.
→ → → *No Compound Identification !*

F. KARG 2025

AOF: Adsorbable Organic Fluorine

= PFAS Monomers & Polymers + other organo-fluorine Compounds; Pesticides, Pharmaceuticals, etc.
→ → *No Compound Identification !*

NTA: Non-Target Analysis = Semi-quantitative Identification of up to 12 000 Compounds: PFAS Monomers

QTA: Quantitative Target Analysis = up to 20-700 Com-pounds: PFAS Monomers

QTA+TA; after TOP Assay (20-200 Compounds: PFCA including transformed polyfluorinated PFAS)

PFAS Analyses

Recommended PFAS Parameters (min.)
+ 5 PFAS ultrashort PFAS

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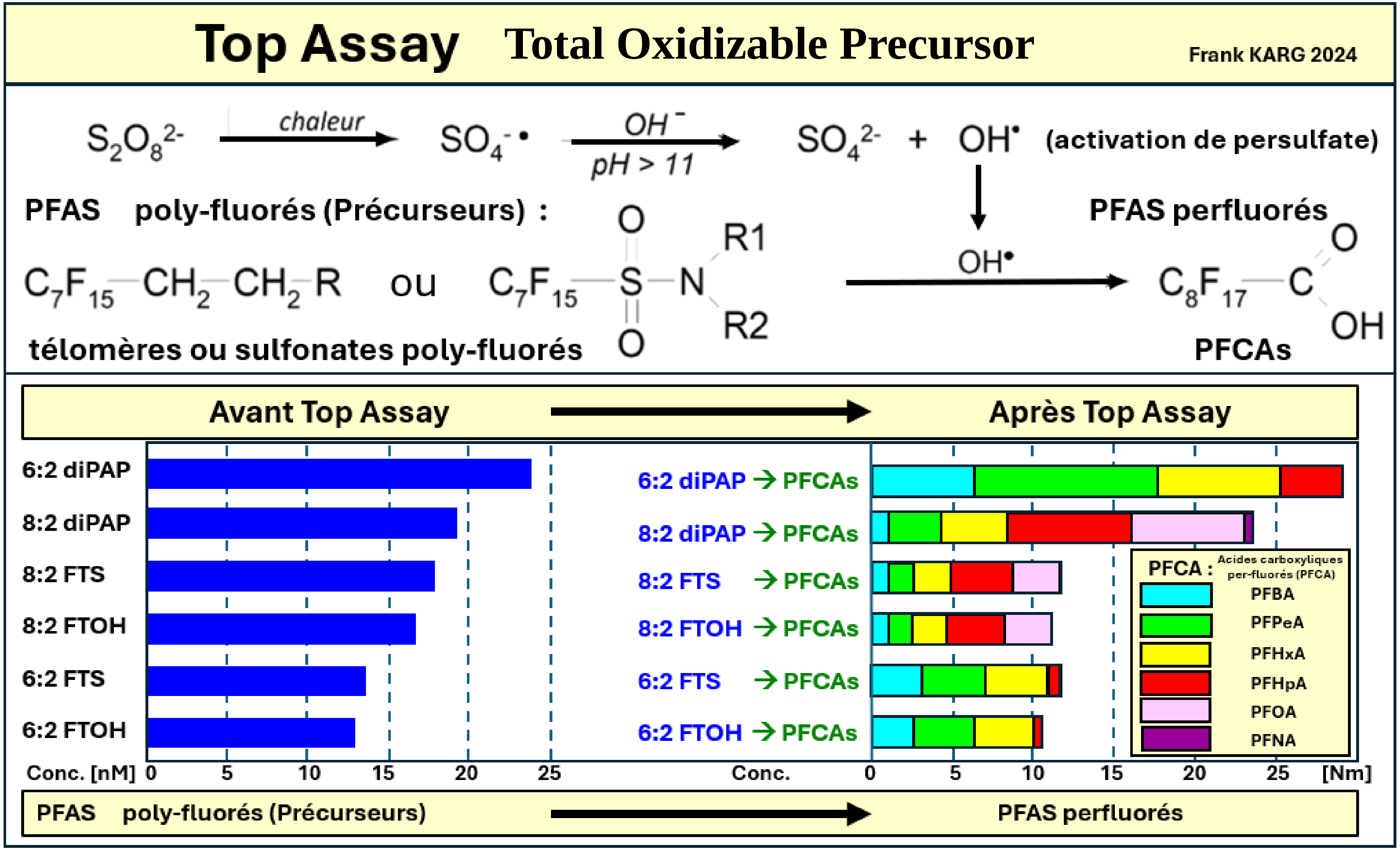
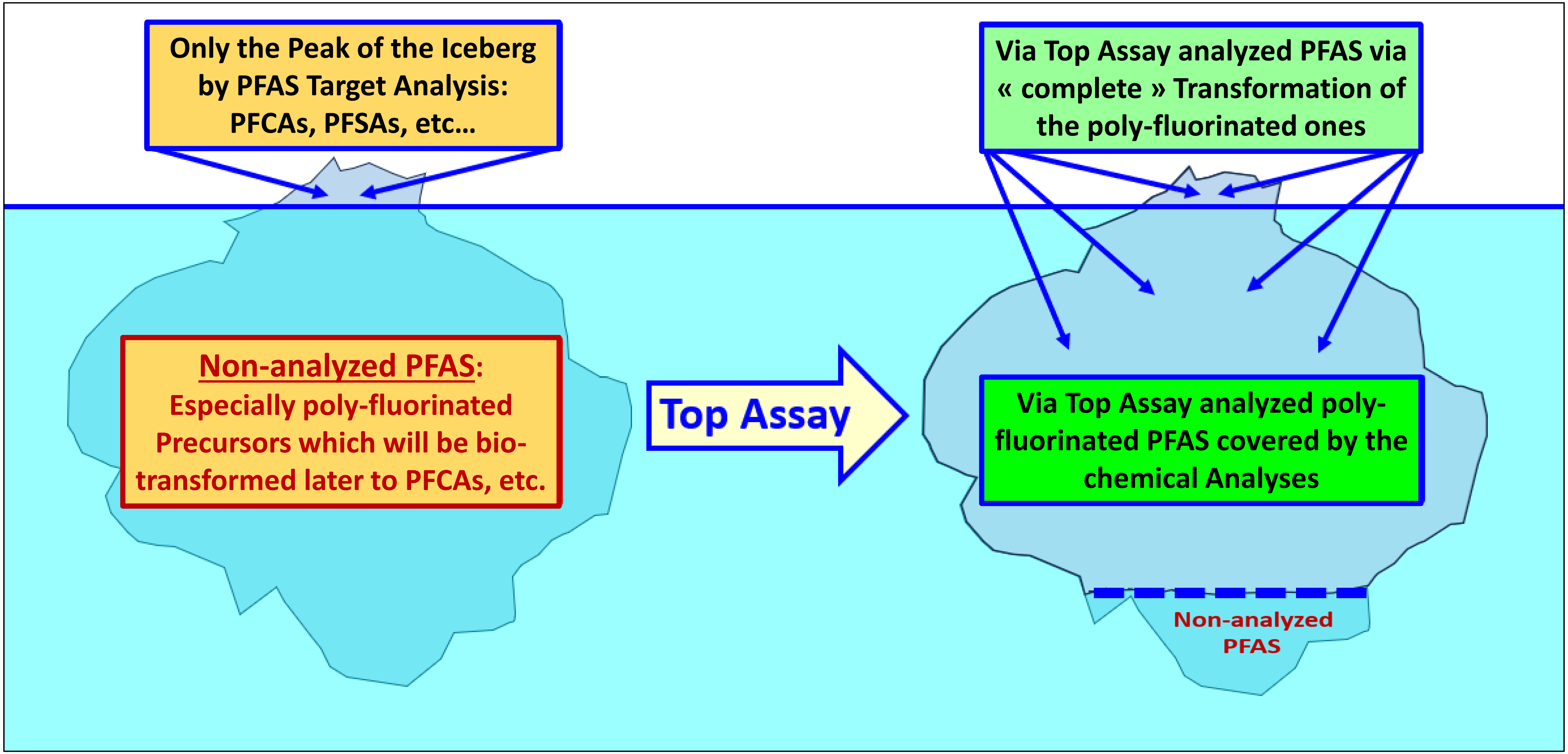
PFAS	LQ Eaux		CAS	VTR	Dir. CE EP2020/ 2184	AM 20/06/23 France
PFBA (perfluorobutanonic acid)	ng/l	1	375-22-4			
PFPeA (perfluoropentanoic acid)	ng/l	5	2706-90-3			
PFHxA (perfluorohexanonic acid)	ng/l	1	307-24-4			
PFHpA (perfluoroheptanonic acid)	ng/l	1	375-85-9			
PFOA lineare (perfluorooctanonic acid)	ng/l	1	335-67-1			
PFOA ramified (perfluorooctanonic acid)	ng/l	1	335-67-1			
PFOA total (perfluorooctanonic acid)	ng/l	1	335-67-1			
PFNA (perfluorononanonic acid)	ng/l	1	375-95-1			
PFDA (perfluorodecanonic acid)	ng/l	1	335-76-2			
PFUnDA (perfluoroundecanonic acid)	ng/l	1	2058-94-8			
PFDoDA (perfluorododecanonic acid)	ng/l	2	307-55-1			
PFTrDA (perfluorotridecanonic acid)	ng/l	1	72629-94-8			
PFTeDA (perfluorotetradecanonic acid)	ng/l	1	376-06-7			
PFHxDA (perfluorohexadecanonic acid)	ng/l	2	67905-19-5			
PFODA (perfluorooctadecanonic acid)	ng/l	1	16517-11-6			
PFBS (perfluorobutane sulfonic acid)	ng/l	1	375-73-5			
PFPeS (perfluoropentane sulfonic acid)	ng/l	1	2706-91-4			
PFHxS linear (perfluorohexane sulfonic acid)	ng/l	1	355-46-4			
PFHxS ramified (perfluorohexane sulfonic acid)	ng/l	1	355-46-4			
PFHxS total	ng/l	1	355-46-4			
PFHpS (perfluoroheptane sulfonic acid)	ng/l	1	375-92-8			
PFOS linear (perfluorooctane sulfonic acid)	ng/l	1	1763-23-1			
PFOS ramified (perfluorooctane sulfonic acid)	ng/l	1	1763-23-1			
PFOS total (acide perfluorooctane sulfonic acid)	ng/l	1	1763-23-1			
PFDS (perfluorodecane sulfonic acid)	ng/l	1	335-77-3			
4:2 FTS (4:2 fluorotelomer sulfonic acid) H4-PFOS	ng/l	1	757124-72-4			
6:2 FTS (6:2 fluorotelomer sulfonic acid)	ng/l	1	27619-97-2			
8:2 FTS (8:2 fluorotelomer sulfonic acid)	ng/l	1	39108-34-4			
10:2 FTS (acide 10:2 fluorotelomer sulfonique)	ng/l	1	120226-60-0			
MePFOSAA (N-methylperfluorooctane sulfonamide acetic)	ng/l	1	2355-31-9			
EtFOSAA (acide N-ethylperfluorooctane sulfonamide aceticue)	ng/l	1	2991-50-6			
PFOSA (perfluoro-n-octanesulfonamide)	ng/l	2	754-91-6			
PFOSA ramified (perfluoro-n-octanesulfonamide)	ng/l	2	754-91-6			
PFOSA total (perfluoro-n-octanesulfonamide)	ng/l	2	754-91-6			
MeFOSA linear (N-méthylperfluorooctanesulfonamide) (MePFOSA)	ng/l	1	31506-32-8			
6:2-FTAB (6 :2 fluorotelomer sulfonamido propyl betaine) Capstone B	ng/l	10	34455-29-3			

PFAS	LQ Eaux		CAS	VTR	Dir. CE EP2020/ 2184	AM 20/06/23 France
MeFOSA ramified (N-méthylperfluoro-n-octanesulfonamide) (MePFOSA)	ng/l	1	31506-32-8			
MeFOSA total (N-méthylperfluoro-n-octanesulfonamide) (MePFOSA)	ng/l	1	31506-32-8			
8:2 DiPAP (8:2 polyfluoroalkyl phosphate diester)	ng/l	1	678-41-1			
HFPO-DA (hexafluoropropyleneoxide dimer acid) / Gen X	ng/l	1	13252-13-6			
EtFOSA linear (N-ethylperfluorooctanesulfonamide) (EtPFOSA)	ng/l	1	4151-50-2			
EtFOSA ramified (N-ethylperfluorooctanesulfonamide) (EtPFOSA)	ng/l	1	4151-50-2			
EtFOSA totale (N-ethylperfluorooctanesulfonamide) (EtPFOSA)	ng/l	1	4151-50-2			
MeFBSAA (perfluorobutanesulfonamide (N-méthyl) acetate)	ng/l	5	159381-10-9			
5:3-FTCA: 5:3 fluorotélomer carboxylic acid	ng/l	1	914637-49-3			
6-2-FTCA: 6:2 fluorotélomer carboxylic acid	ng/l	5	53826-12-3			
8:2 FTUCA (2H-perfluoro-2-decenoique acid)	ng/l	1	70887-84-2			
DONA (4,8-dioxa-3H-perfluorononanonic acid) ADONA	ng/l	1	919005-14-4			
MeFBSA (n-methylperfluorobutanesulfonamide)	ng/l	1	68298-12-4			
PFBSA (perfluorobutanesulfonamide)	ng/l	1	30334-69-1			
PFECHS (perfluoro-4-éthylcyclohexanesulfonic acid)	ng/l	1	646-83-3			
PFNS (perfluorononane sulfonic acide)	ng/l	1	68259-12-1			
PFDoDS (perfluorododecane sulfonic acid)	ng/l	1	79780-39-5			
6:2 phosphate fluorotelomeric diester. 6:2 diPAP	ng/l	10	57677-95-9			
6:2 8:2 phosphate fluorotelomeric diester 6:2 8:2 diPAP	ng/l	10	943913-15-3			
PFHxSA (perfluorohexanesulfonamide)	ng/l	1	41997-13-1			
PFUnDS (perfluoroundecane sulfonic acid)	ng/l	2	749786-16-1			
PFTrDS (perfluorotridecane sulfonic acid)	ng/l	2	791563-89-8			
EtFOSE (2-(N-ethylperfluoro-1-octanesulfonamido)-ethanol)	ng/l	5	1691-99-2			
MeFOSE (2-(N-methylperfluoro-1-octanesulfonamido)-ethanol)	ng/l	5	24448-09-7			
NFDHpA (Nonafluoro-3,6-dioxaheptanoic acid)	ng/l	1	151772-58-6			
PFMPA (Perfluoro-3-methoxypropanoic acid)	ng/l	1	377-73-1			
PFMBA (perfluoro-4-methoxybutanoic acid)	ng/l	1	863090-89-5			
C6O4 (Perfluoro([5-methoxy-1,3-dioxolan-4-yl]oxy)acetic acid)	ng/l	10	1190931-41-9			
6:2-FTOH (6:2 fluorotelemer alcohol) FHET	ng/l	20	647-42-7			
8:2-FTOH (8:2 fluorotelemer alcohol) FOET	ng/l	10	678-39-7			
PFAS Ultrashorts :						
TFA (trifluoroacetic acid)	ng/l	10				
PFPrA (perfluoropropanoic acid)	ng/l	10				
TFMS (trifluoromethanesulfonic acid)	ng/l	10				
PFES (perfluoroethanesulfonic acid)	ng/l	10				
PFPrS (perfluoropropanesulfonic acid)	ng/l	10				

Considering of all poly-fluorinated PFAS as final per-fluorinated PFCAs



Analyses PFAS sans et avec Top Assay



Overview of existing PFAS treatment technologies concerning Soil, Water and Air

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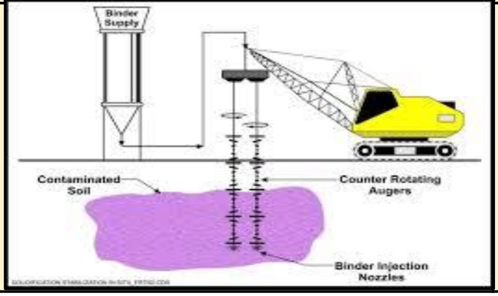
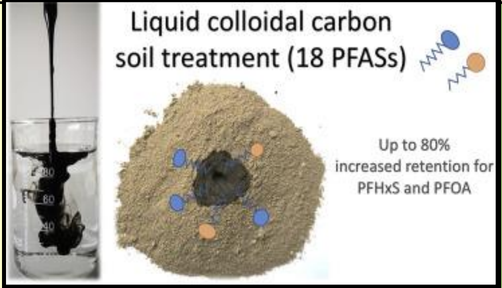
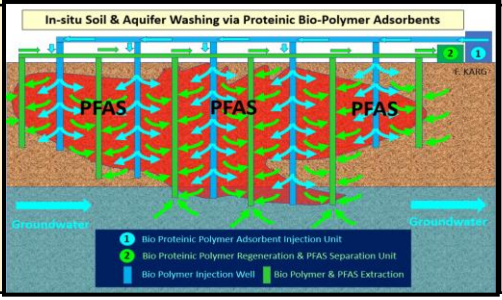
PFAS: Dépollutions des sol, des sediments et des eaux (souterraines, lixiviats, etc.)					Frank KARG
Matrice	***Technologie***		***Advantage***	***Inconvénients***	***Remarques***
1. Soil	**On-site & off-site:** ➢ **Excavation & Confinement / Landfill (Dig & Dump)**		Rapid Site Remediation.	Very Expensive. Needs excava-tion. No sustain-able solution.	Lots of Landfills don't accept PFAS contamin-ated soils (>50 mg/kg)
2. Soil	**On-site:** ➢ **Capping / Surface Sealing to avoid Leaching to Ground-water**		Rapid cut-off concerning Exposure Path-ways & Leachate to Groundwater	Site use restric-tions /Servitudes No sustainable solution.	Lots of Authorities don't accept this solution.
3. Soil	**In-situ:** ➢ **Excavation & Treatment: Physical, Chemical, Thermic-ally (Washing, ISCO, Thermal Destruction, etc.)**		In-situ-Site Remediation	Relatively Expensive by Electricity Costs. Gas treatment is needed.	Feasibility Study is need-ed concerning sub-soil condi-tions.
4. Soil	**On-site, off-site or in-situ** ➢ **Stabilization with cationic clays, Zeolites, etc. to avoid Leaching to Groundwater**		Avoid leachate to Groundwater.	Very Expensive. Needs potentially excavation.	Feasibility Study is need-ed concerning Stabilization ingredients.

Overview of existing PFAS treatment technologies

PFAS: Dépollutions des sol, des sediments et des eaux (souterraines, lixiviats, etc.)

Frank KARG

Matrice	*Technologie*	*Advantage*	*Inconvénients*	*Remarques*
5. Soil	**On-site & off-Site:** ➢ **<u>Thermal Desorption</u> up to 1 200 °C:** JACOBS – William DiGuiseppi et al. 	Relatively rapid Site Remediation.	Expensive. Needs excava-tion. No sustain-able solution (off-gas, CO_2…).	Lots of Authorities don't accept PFAS soils. (https://www.enviro.wiki/images/5/50/DiGuiseppi2019.pdf)
6. Soil	**Off-site:** ➢ **<u>Incineration</u> up to 1 200 °C** 	Relatively rapid Site Remediation.	Very Expensive. Needs excavation. No sustain-able solution (off-gas, PFDD-F Emissions)	Lots of Inciner-ators don't accept PFAS contaminated soils.
7. Soil	**In-Situ:** ➢ **<u>Immobilization</u> with colloidal activated carbon (CAC):** Plume Stop/ Regenesis or MattCARE 	In-situ-Site Remediation by injection of CAC.	A feasibility stu-dy must show the needed ad-sorption capacity & aquifer needs	Feasibility Study is need-ed concerning sub-soil condi-tions.
8. Soil & Aquifer	**In-situ & ex-situ:** ➢ **<u>In-situ soil Washing</u> with proteinic Bio-polymers, beta-Cyclodextrines, etc.:** Sensatec, HPC-INTERNATIONAL 	Avoid excava-tion. Appliable for saturated & non-saturated Zones.	Needs technical-economic Feasibility Study.	Washing detergents or Agents must be tested.

Overview of existing PFAS treatment technologies

PFAS: Soil -Water and Aquifer Remediation Technologies (Wastewater, Leachate, Groundwater, etc.) Frank KARG					
Matrice	***Technologie***		***Advantage***	***Inconvénients***	***Remarques***
9. Soil	**In-Situ & ex-situ:** ➢ **<u>Immobilization</u> with Clays and Zeolites:** CETCO & ZEOCEL and by DND Biotech –Italy	**Natural Modified Zeolites**  	In-situ-Site Remediation by injection of Clays or Zeolites	A feasibility study must show the needed adsorption capacity & aquifer needs	Feasibility Study is needed concerning sub-soil conditions.
10. Water	**Ex-situ:** ➢ **<u>Extraction by biodegradable Floculant</u> & Precipitation: PerfluorAd /** Cornelsen-TRS,	 	Efficient Water treatment, useable also for soil & sediment washing.	Needs P&T & technical-economic Feasibility Study (pH, salinity, co-pollutants + GAC Polishing ?...).	Different Agents must be tested.
11. Water	**Ex-situ:** ➢ **<u>Modified Clay</u> / Adsorbens:** CETCO & ETEC2: **Fluorosorb**	 	Efficient Water treatment.	Needs P&T & technical-economic Feasibility Study (pH, salinity, co-pollutants...).	Different Agents must be tested.
12. Water	**Ex-situ:** ➢ **<u>Ion Exchange Resins (IX)</u>** **Lewatit® TP 108 DW** (+for short PFAS) & Lewatit® K 6362 (Wastewater) & Lewatit ® MP 62 WS/LANXESS, Sorbix A3F resin & **Sorbix LC4 & Sorbix RePure LC /ETEC$_2$, Purofine® PFA-694** & Purofine®- PFA694E/ Pyrolite & ECOLAB, Amberlite PSR2 Plus / DuPont, CalRes 2301/Calgon Carbon Corp., SIR-110-HP/ Resin Tech Inc., Fluoro-Sorb® / CETCO, RemBind™ / ZILTEC		Efficient Water treatment if pH is not alkaline. Depends on salinity, co-pollutants.	Needs P&T & technical-economic Feasibility Study: pH, salinity, co-pollutants, GAC needs, ?	Different Agents and IX (mixtures) must be tested. A: Single used IX: → Incineration need B: Regenerable IX → With alkaline pH

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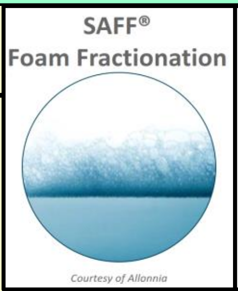
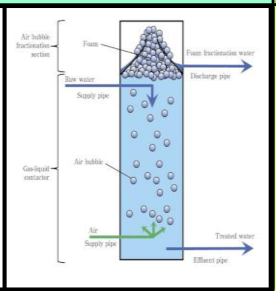
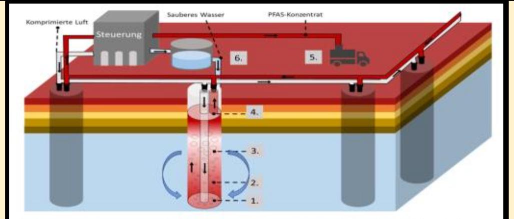
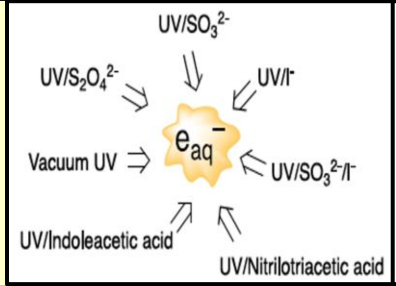
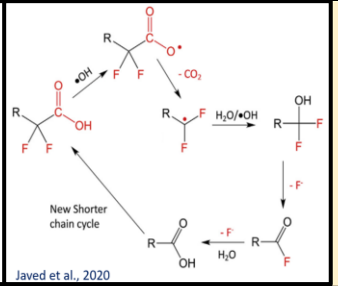
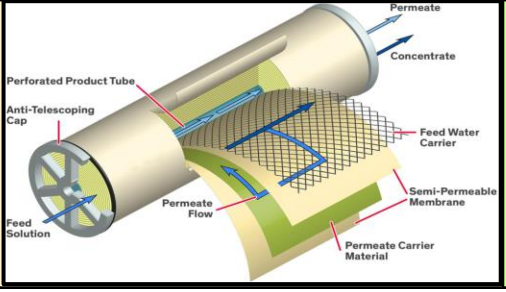
PFAS: Dépollutions des eaux (souterraines, lixiviats, etc.) Frank KARG				
Matrice	***Technologie***	***Advantage***	***Inconvénients***	***Remarques***
13. Water	**Ex-situ:** ➢ **<u>Foam Fractioning</u> / Air-Water-Interface Foam / Concen-tration in Bubble Interfaces:** ALLONIA, SAFF®, etc.  	Efficient Water treatment, useable also for soil & sediment washing.	Needs technical-economic Feasibility Study. Principally for PFAS > C6.	Different Agents must be tested.
14. Water	**In-situ:** ➢ **<u>Downhole Foam Fractioning:</u>** OPEC Systems / Australia  Abb. 18: Prinzip des In- situ Schaumfraktionierung-Verfahrens. 1: Komprimierte Luft wird an der Basis des Brunnens eingetragen. 2: PFAS schäumt aus dem Grundwasser aus, 3: Luftblasen tragen den Schaum zur Oberfläche. 4: Schaum wird mittels einer speziellen Vorrichtung abgezogen und zur Anlage gepumpt, in der eine weitere Aufkonzentrierung stattfindet. 5: Konzentrierte PFAS-Lösung wird zum vollständigen externen Abbau abtransportiert, 6: Das gereinigte Wasser wird in den Aquifer zurückgepumpt.	Potentially Efficient Water treatment.	Needs P&T & technical-econo-mic Feasibility Study.	Only one provider in 2024
15. Water	**Ex-situ:** ➢ **<u>Photolysis by UV/ H_2O_2</u> / Advanced Reduction Process (ARP):** Tree Water  	Mineralization via hydrated OH-Radicals. .	Experimental Status in 2024. Needs technical-eco-nomic Feasiblity Study.	Creation of hydraed electrons (e-aq).Pro-duction by adding a reducing agent (iod-ides, thiosulfate, sulfite, etc.).
16. Water	**Ex-situ:** ➢ **<u>Reverse Osmosis (RO):</u>** (Wastewater): SIMPEC *(+SARPI-VEOLIA)* 	Efficient Water treatment in dependance of organic load.	Needs P&T & technical-econo-mic Feasibility Study (organic lmoad, etc.).	10mS·cm^{-1}-conductivity and a total organic carbon concentration of 1100 mg·L^{-1} could be treated by RO

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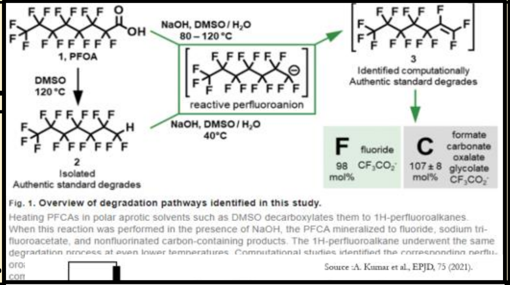
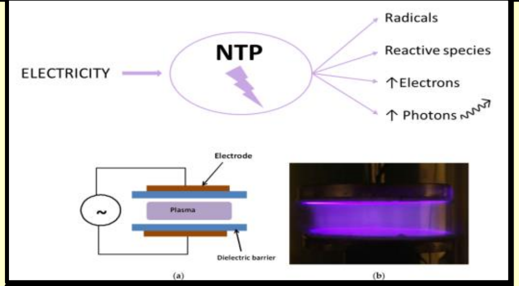
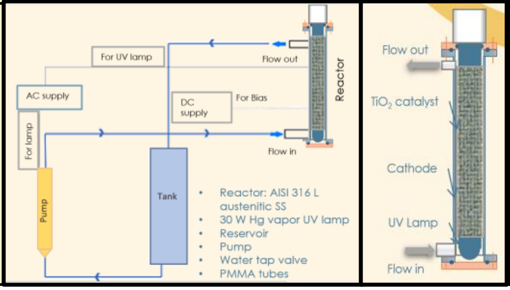
Overview of existing PFAS treatment technologies

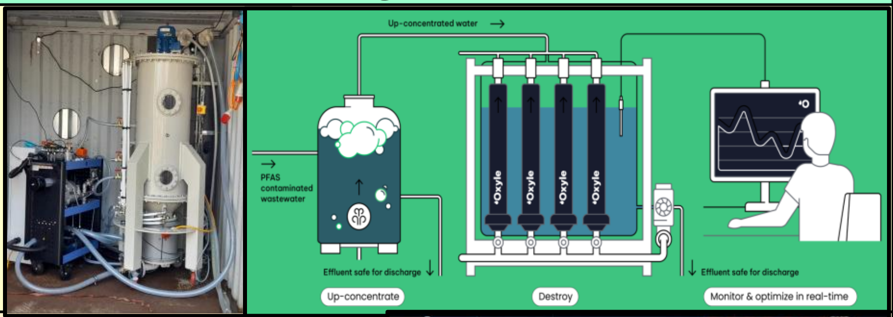
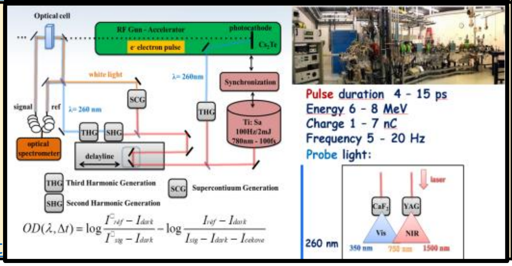
HPC

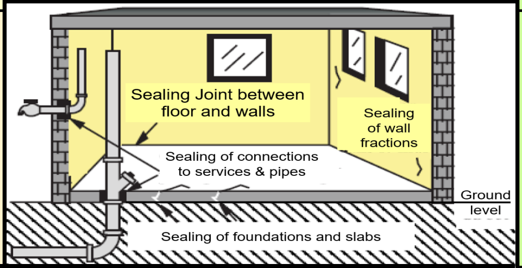
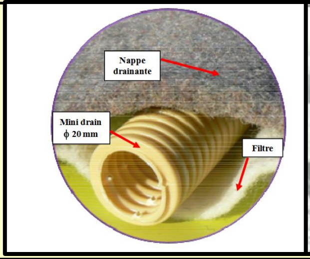
PFAS: Dépollutions des eaux (souterraines, lixiviats, etc.) Frank KARG				
Matrice	***Technologie***	***Advantage***	***Inconvénients***	***Remarques***
17. Water	**Ex-situ (+ in-situ injections):** ➢ **Activated Carbon (GAC), Powdered Activated Carbon (PAC) & Biochars:** Purolite, etc. (+Sensatec) 	Efficient Water treatment depending of pollutant Cocktail (ultra short PFAS ?)	Needs technical-economic Feasibility Study: pH, salinity, co-pollutants, + GAC needs?	Different combinations (+ Adsorption Resins ?) must be tested.
18. Water	**Ex-situ:** ➢ **Low Temperature Mineralization – Decarboxylation & Defluorination** (80° - 120°C – Heating with NaOH & DMSO Solv. 	Efficient Water treatment in Dimethyle-sulfoxide, useable for soil & sediment washing.	Needs technical-economic Feasibility Study. Commercial Availability not granted.	Advanced Research Status: Brittany TRANG et al. 2022 (https://www.science.org/doi/10.1126/science.abm8868).
19. Water	**Ex-situ:** ➢ **Non-Thermal Plasma (NTP) Destruction:** Tectero BV / Belgium LSPM / Sorbonne 	Efficient Water treatment under conditions.	Needs technical-economic Feasibility Study (Co-pollutants, alkanity…?). Electricity Costs ?	Advanced Research Status with pilots (2024).
20. Water	**Ex-situ:** ➢ **Photo-electrocatalytic Advanced Oxidation (PEC) Processes:** Capture – Italia 	Efficient PFAS Destruction & Mineralization Process (> 99 %).	Needs technical-economic Feasibility Study: pH, salinity, co-pollutants. Pilot exist (2024).	Usable for contaminated Groundwater and for WWTP (Wastewater Treatment Pants).

Overview of existing PFAS treatment technologies

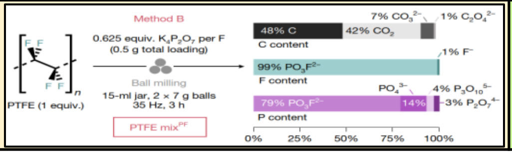
PFAS: Dépollutions des eaux (souterraines, lixiviats, etc.)

Frank KARG

Matrice	*Technologie*	*Advantage*	*Inconvénients*	*Remarques*
21. Water	**Ex-situ:** ➢ **Catalytic Remediation:** Oxyle/CIMO 	Efficient PFAS Destruction & Mineralization Process (> 99 %).	Needs technical-economic Feasibility Study: pH > 7, salinity, co-polluants, Catalysts Case Studies exist.	Case Studies in Switzerland (2024).
22. Water	**Ex-situ:** ➢ **Supercritical Destruction:** ELIXIR / Arianne Group 	Efficient Water treatment for all kind of organic pollutants.	Needs technical-economic Feasibility Study (Co-polluants, alkanity…?). Very expensive / Electricity Costs !	Advanced Research Status with some references (2024).
23. Water	**Ex-situ & in-situ:** ➢ **Sonolysis (Ultrasonic):** SERDP – ESTCP Craig Divine, Ph.D. / Sonolysis in Situ Reactor for Treatment within an HRX well https://serdp-estcp.mil/projects/details/b178d35c-2fa5-443b-a2db 	Efficient Water treatment by 700-kHz sonolysis	Needs technical-economic Feasibility Study (Co-polluants, etc.).	some references (2024). HRX-well (low permeability) P.R. Kulkarni . 2022 https://ascelibrary.org/doi/10.1061/%28ASCE%29EE.1943-7870.0002064
24. Water	**Ex-situ (& in-situ):** ➢ **Ionization Radiation / Radiolysis:** Uni Paris-Saclay / CNRS /Mehran MOSTAFAVI https://www.inc.cnrs.fr/fr/cnrsinfo/comment-booster-la-degradat 	Efficient Water treatment by 6 – 8 MeV RaAdiolysis	Needs technical-economic Feasibility Study (Co-polluants, etc.).	Research Status (2024). HRX-well Mehran MOSTAFAVI: 2024 https://www.inc.cnrs.fr/fr/cnrsinfo/comment-booster-la-degradation-des-pfas-par-radiolyse

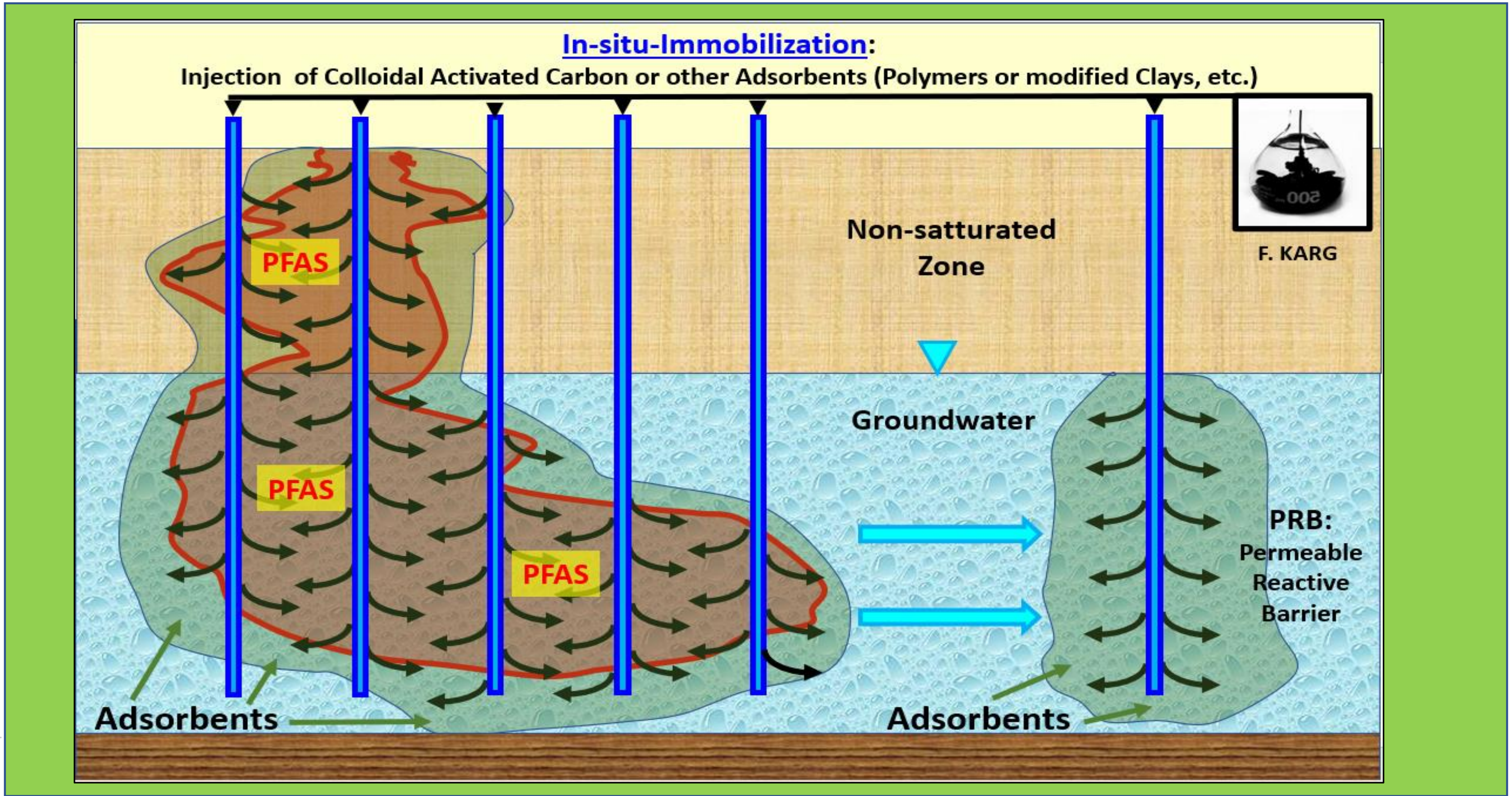
<table>
<tr><th colspan="5">PFAS: Dépollutions des gaz du sol et traitement de l’eau
Frank KARG</th></tr>
<tr><th>Matrice</th><th>Technologie</th><th>Advantage</th><th>Inconvénients</th><th>Remarques</th></tr>
<tr><td>25. Soil gas</td><td>In-situ:
➢ <u>Soil Vapor Extraction (SVE)</u>: HPC International
</td><td>Efficient for volatile PFAS as 6:2-FTOH, 8:2-FTOH, TFA, etc.</td><td>Needs technical-economic Feasibi-lity Study (Sub soil Permeabilities, etc.)</td><td>Standard Remediation Technology.</td></tr>
<tr><td>26.Ambient Air</td><td>In-situ:
➢ <u>Sub Slab Extraction (under Foundations)</u>: HPC International

</td><td>Efficient for volatile PFAS as 6:2-FTOH, 8:2-FTOH, TFA, etc.</td><td>Needs technical-economic Feasibi-lity Study (Sub soil Permeabilities, etc.)</td><td>Standard Remediation Technology.</td></tr>
<tr><td>27. Soil gas & Ambient Air</td><td>In-situ:
➢ <u>Gas drainages (under Foundations)</u>: HPC International


</td><td>Efficient for volatile PFAS as 6:2-FTOH, 8:2-FTOH, TFA, etc.</td><td>Needs technical-economic Feasibi-lity Study (Sub soil Permeabilities, etc.)</td><td>Standard Remediation Technology.</td></tr>
<tr><td>28. Soil gas & Ambient Air</td><td>In-situ:
➢ <u>Building Sealings)</u>: HPC International

</td><td>Efficient for volatile PFAS as 6:2-FTOH, 8:2-FTOH, TFA, etc.</td><td>Needs technical-economic Feasibi-lity Study (Sub soil Permeabilities, etc.)</td><td>Standard Remediation Technology.</td></tr>
<tr><td>29.PFAS-Polymers</td><td>➢ Phosphate-enabled mecano-chemical destruction
Long Yang et al. 2025

</td><td>Efficient for polymers: PTFE</td><td>Needs t Feasibility Study (</td><td>Research status</td></tr>
</table>

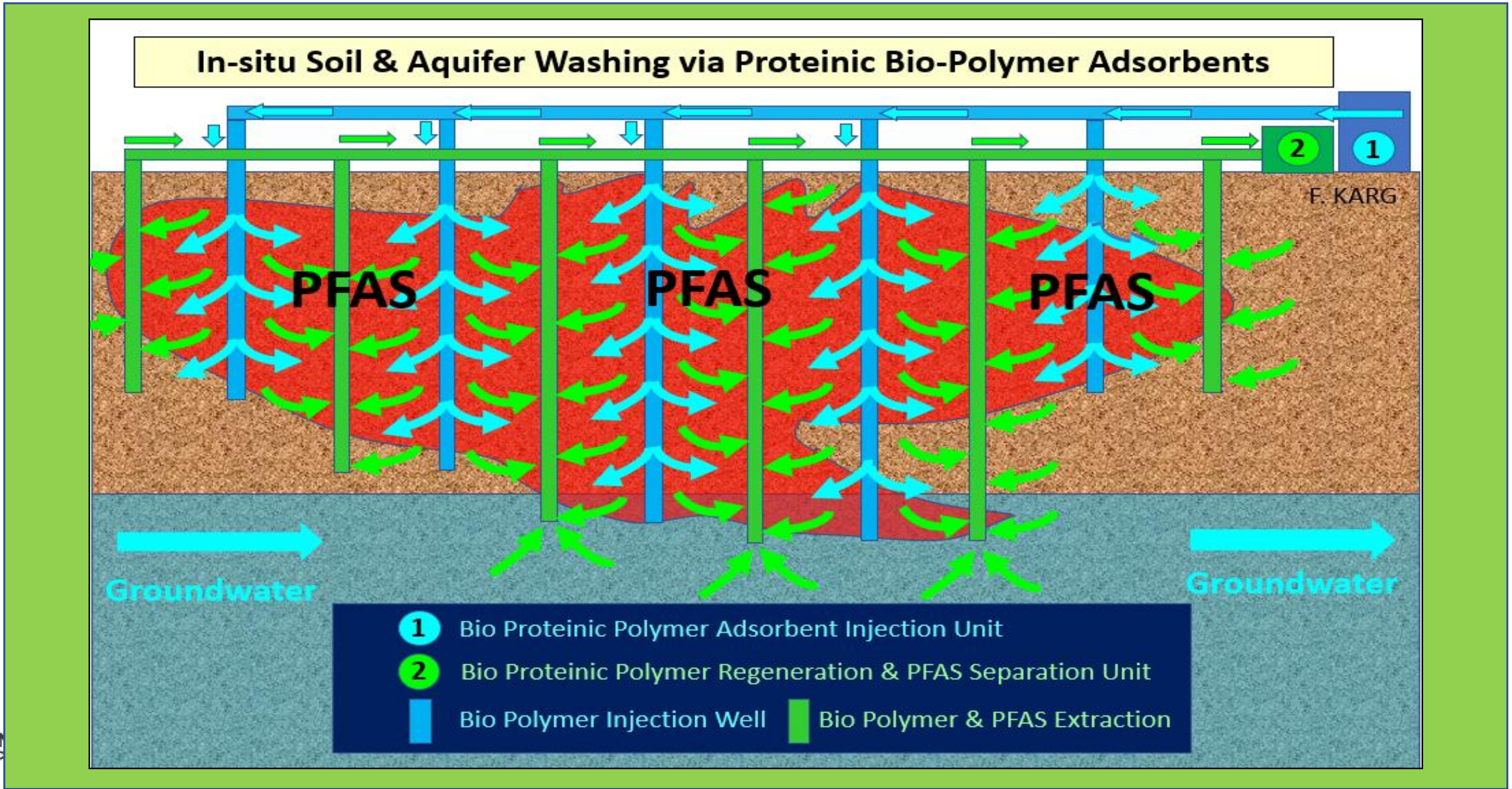
Dépollution in-situ :

➢ **Imobilization in-situ via Charbon Actif Colloidal (HPC)**

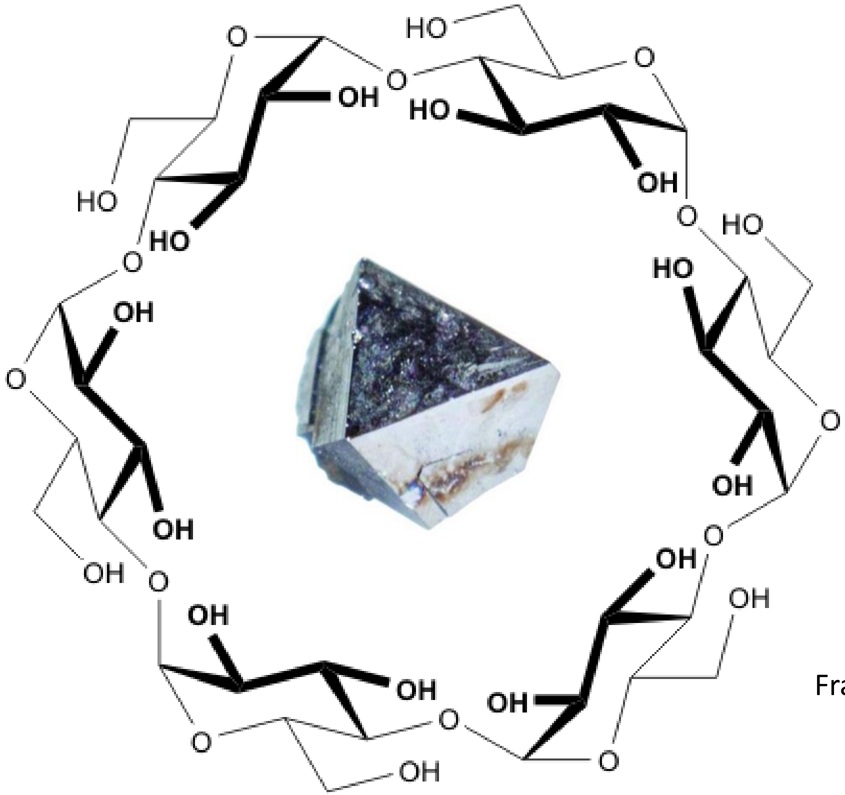


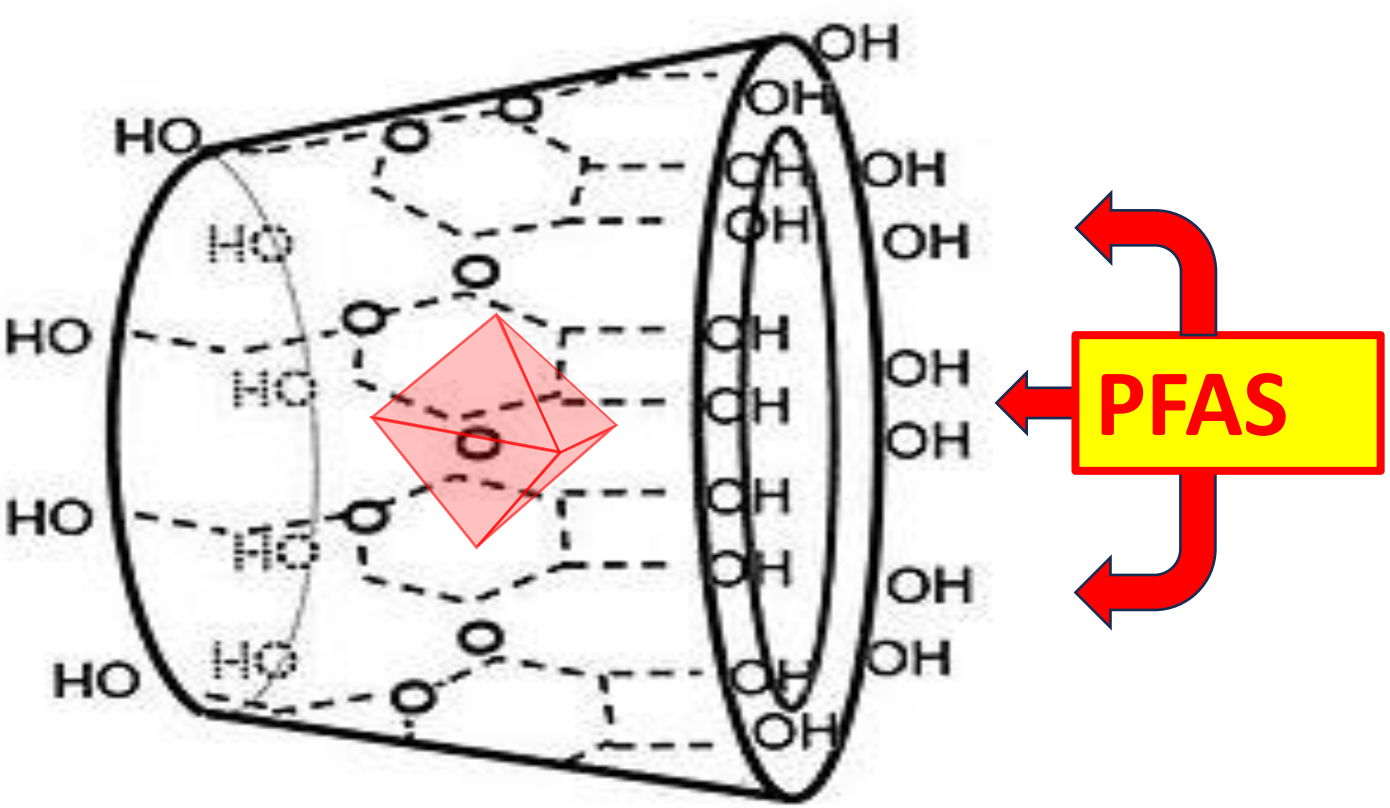
Dépollution in-situ :

➢ **Lavage in-situ par Bio-polymers protéiniques (HPC)**

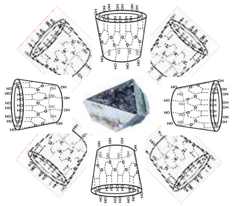


n-Magnetite Crystals coated by Tunnel - Beta-Cyclodextrins





Frank KARG, 2024



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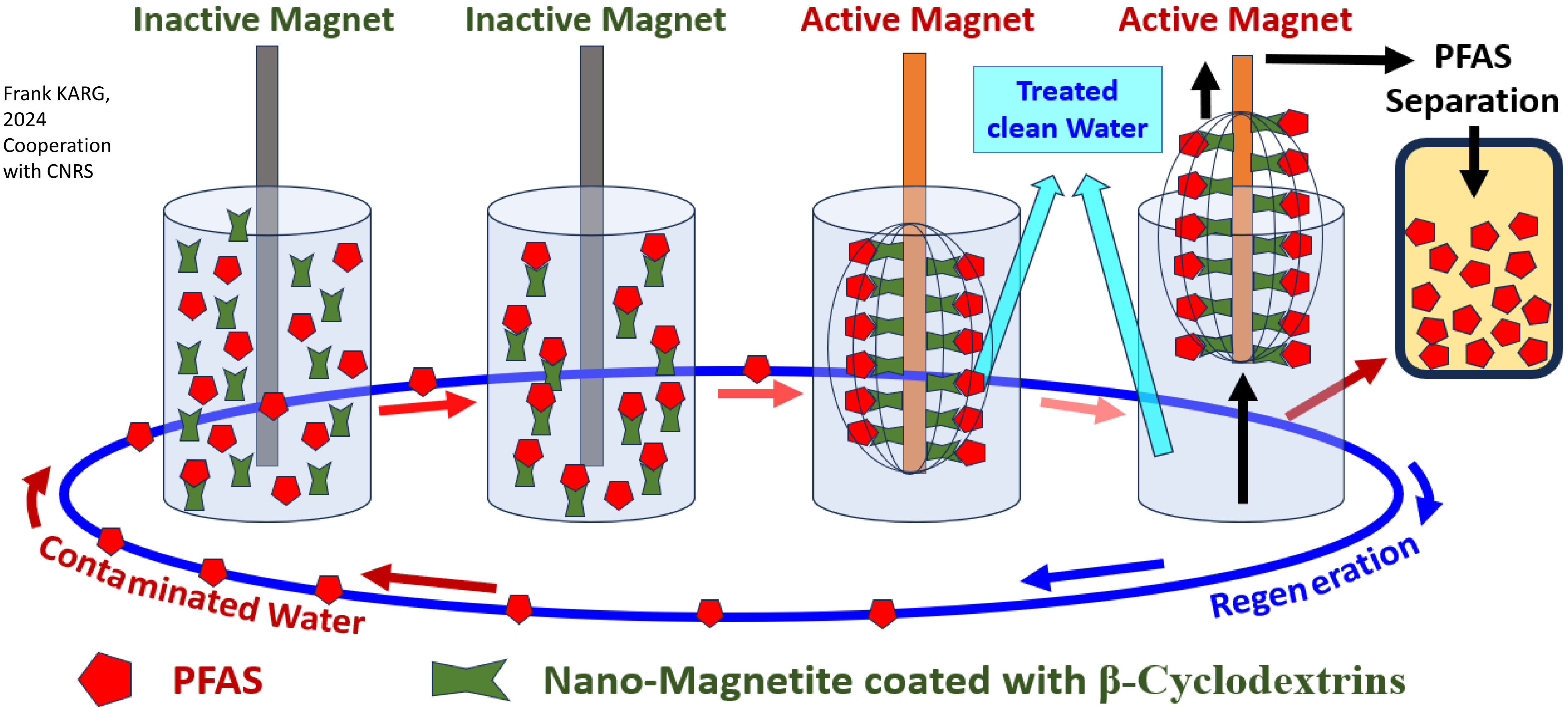
PFAS Water Purification via Nano-Magnetite coated with β-Cyclodextrins

Frank KARG, 2024 Cooperation with CNRS



Overview of existing PFAS treatment technologies concerning Soil, Water and Air

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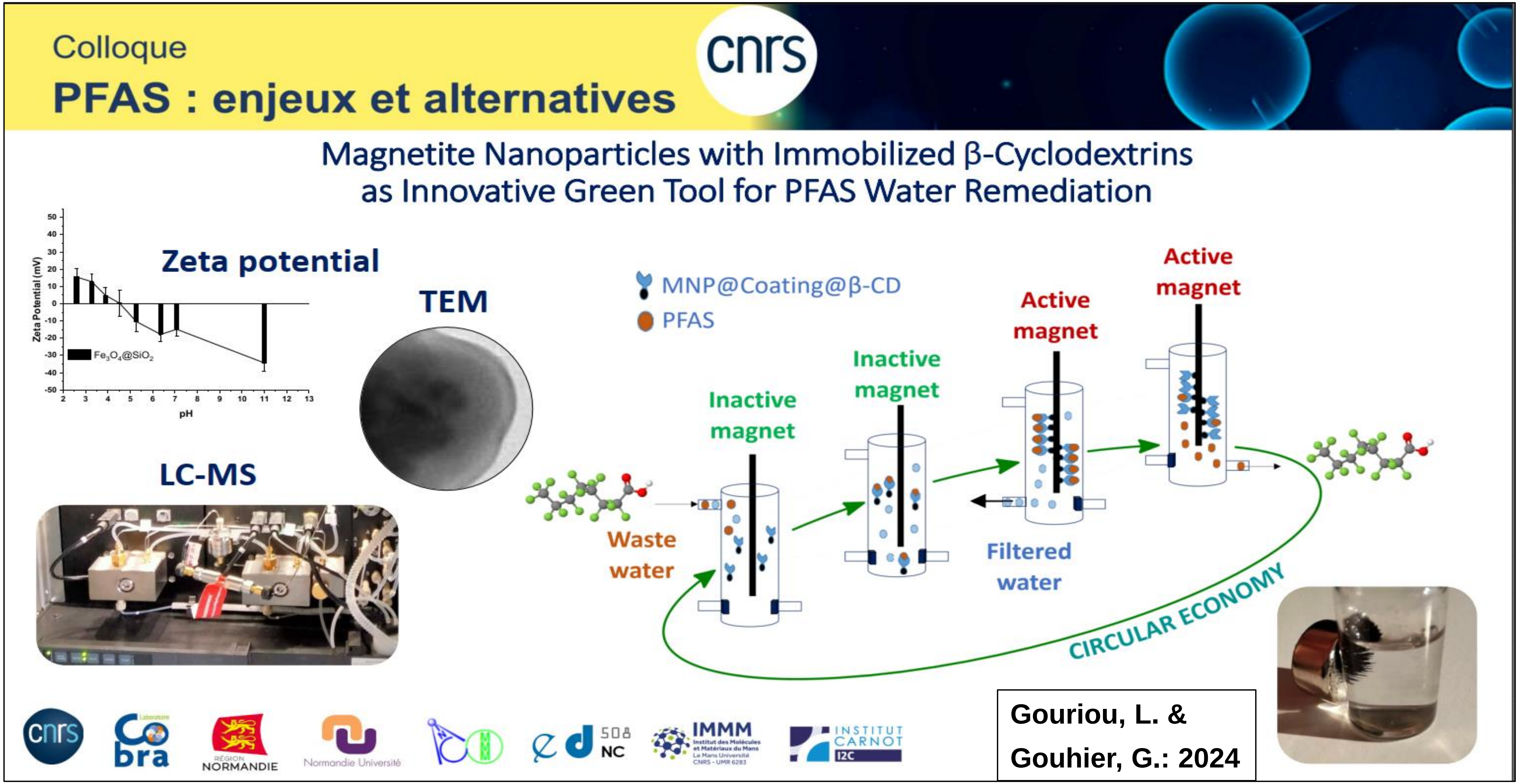

Gouriou, L. & Gouhier, G.: 2024

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Overview of existing PFAS treatment technologies concerning Soil, Water and Air

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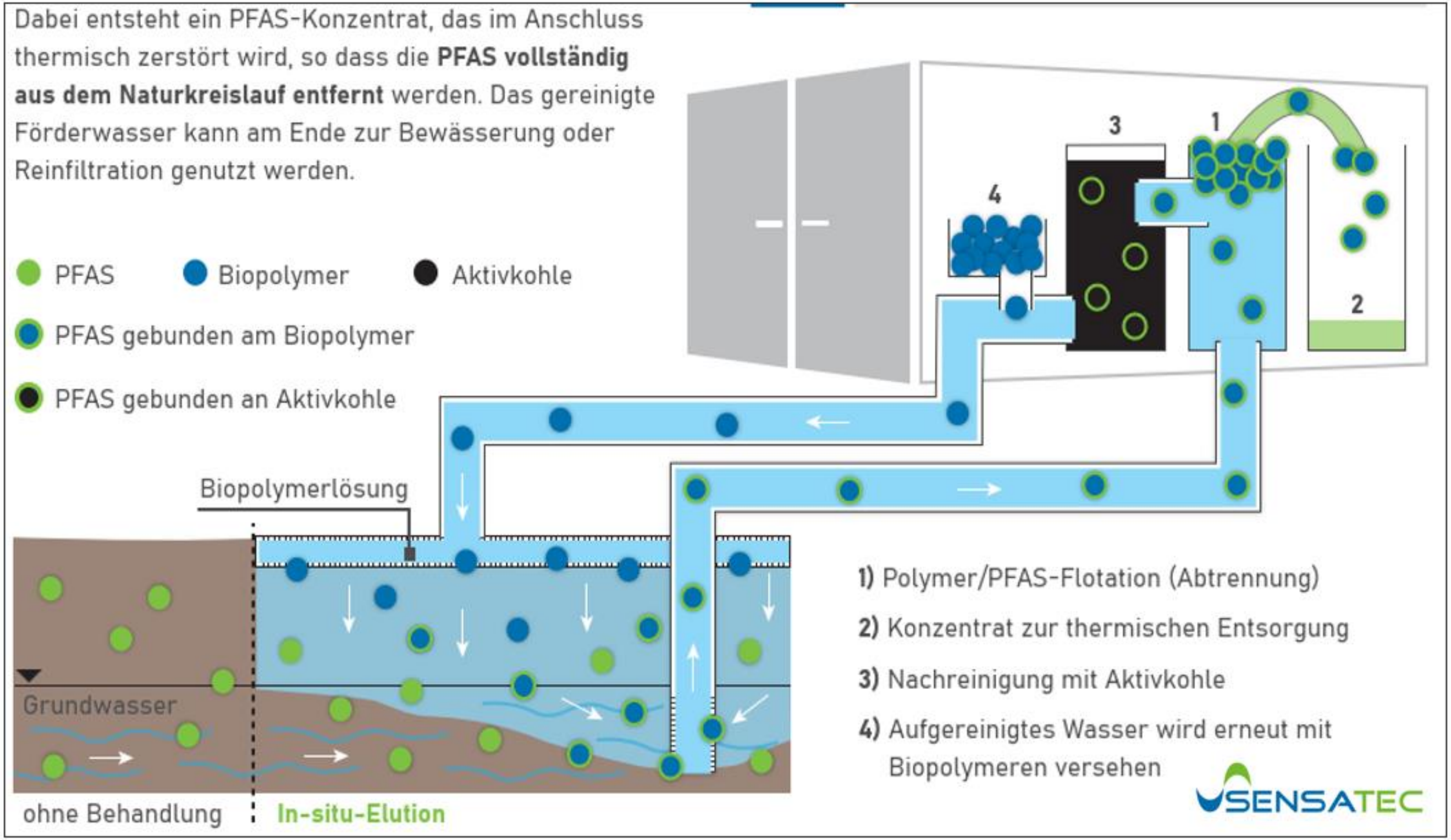
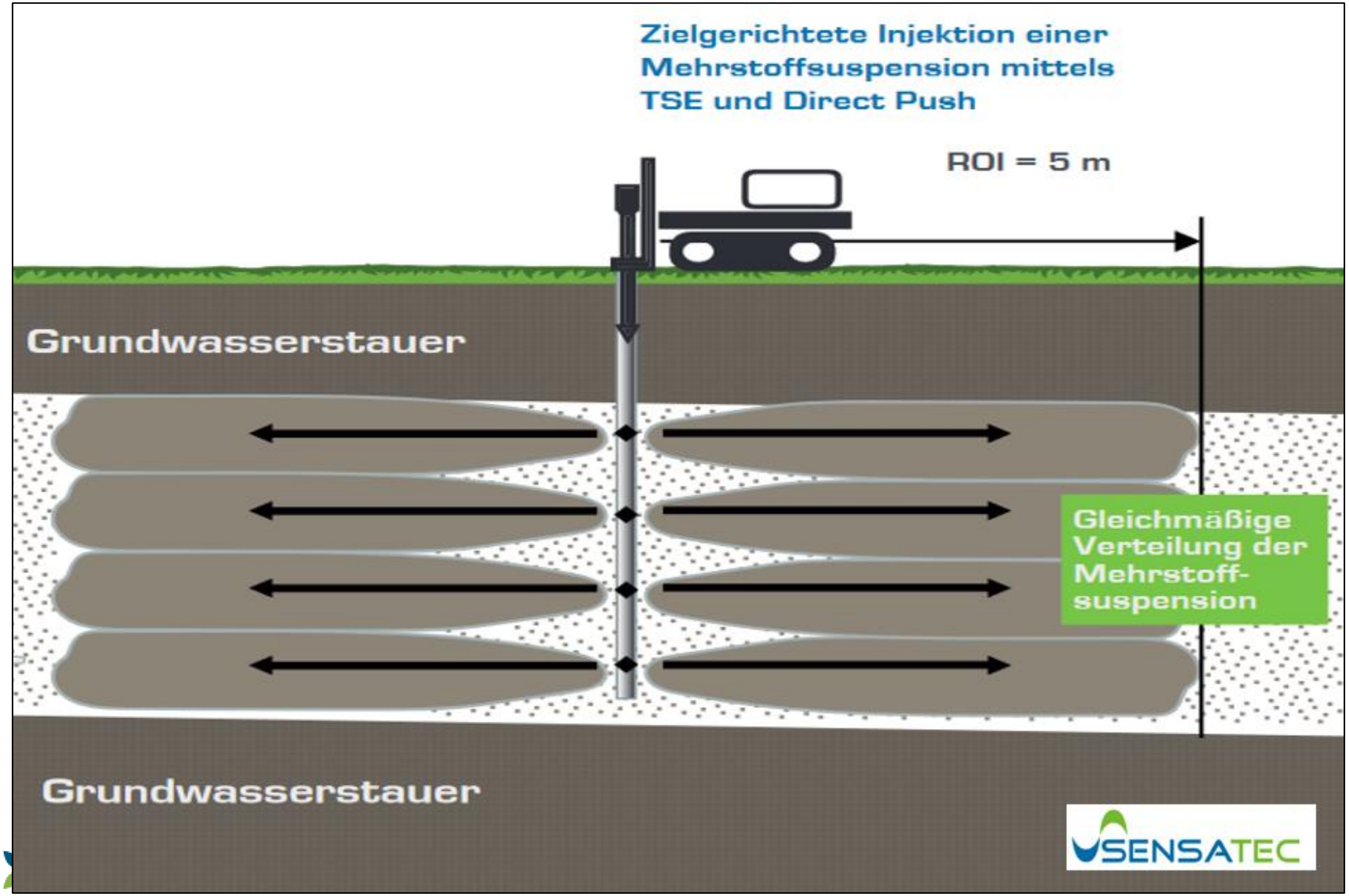
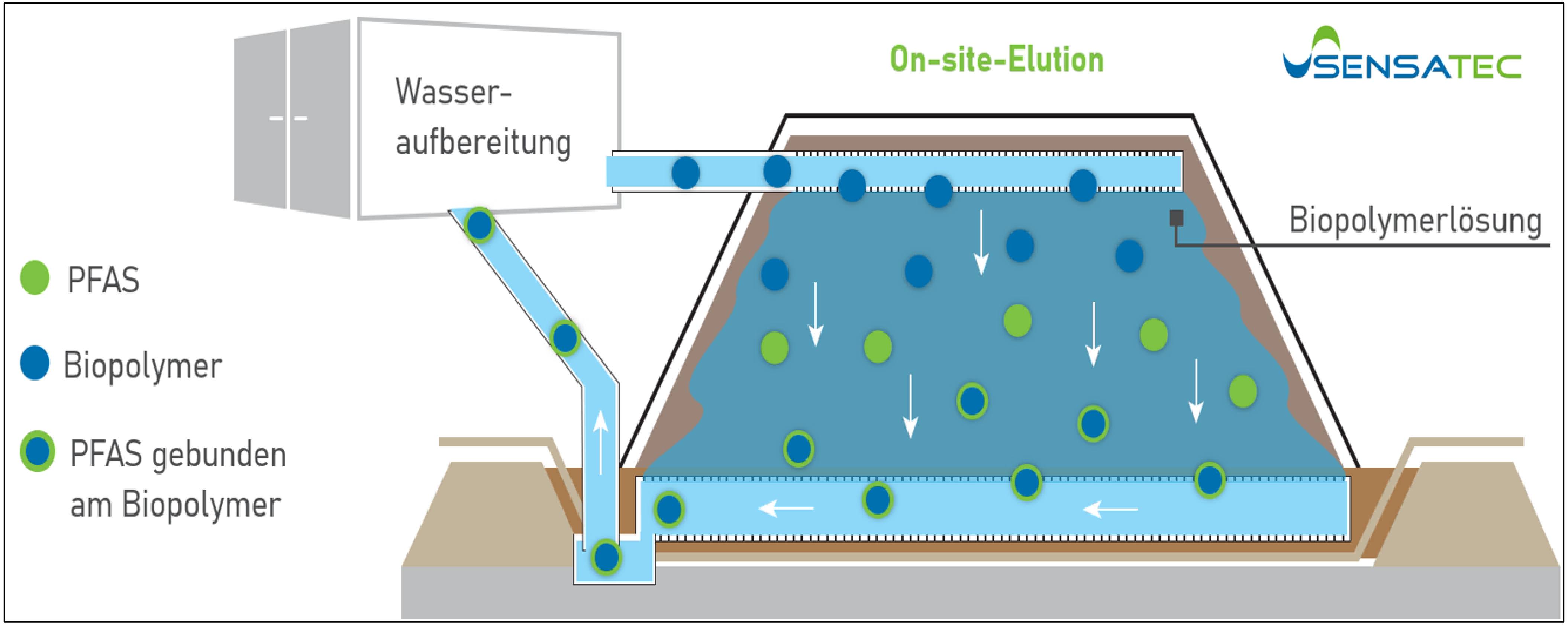


Lavage in-situ des PFAS via des Biopolymeres proteiniques



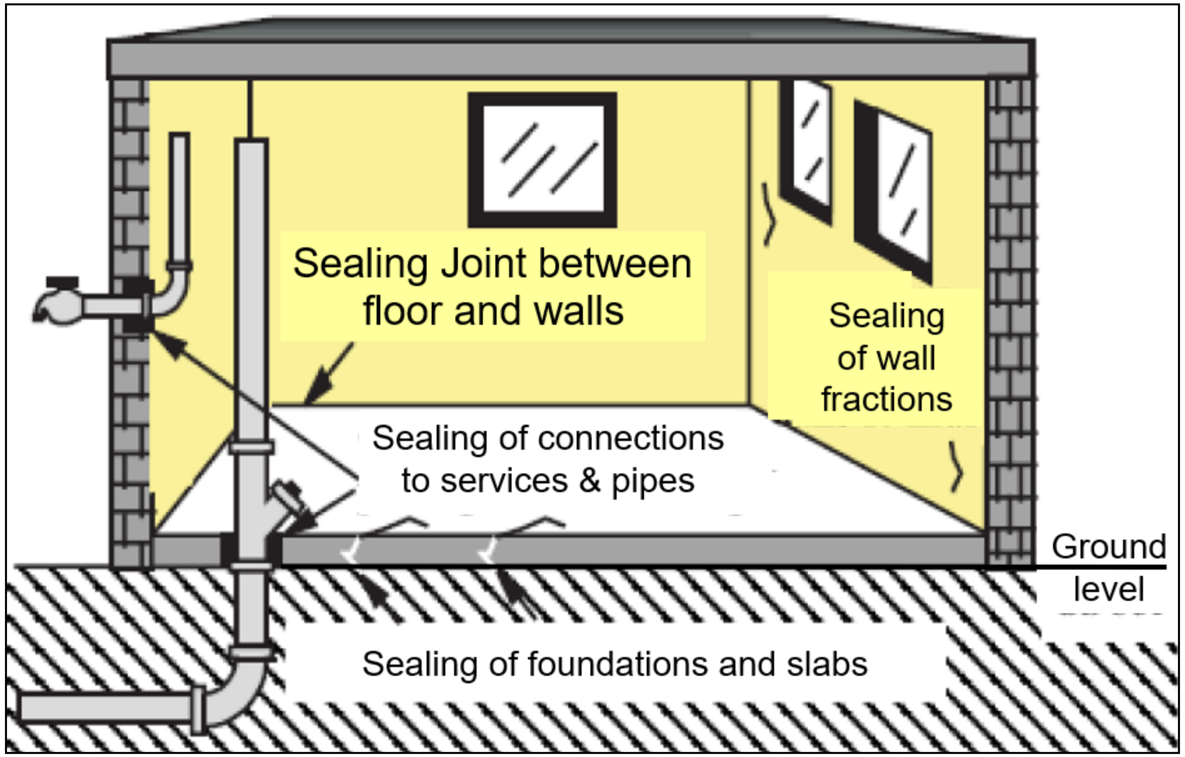
Lavage in-situ des PFAS

Perméabilisation au préalable via des Injections TSE



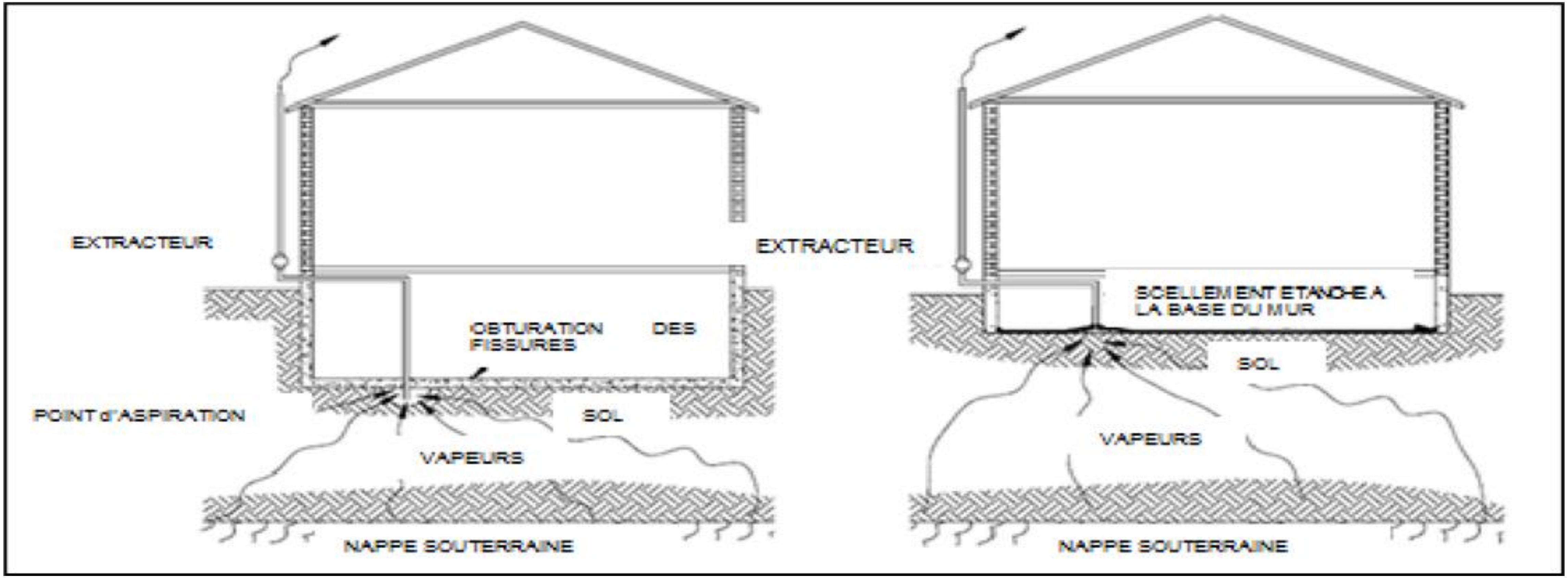
Lavage
On-Site des
PFAS
via des
Biopolymeres
proteiniques

Mesures constructives de protection de l'Air Ambiant contre les Gaz du Sol (FTOH, COHV, etc.): Etanchéifications, Ventilations, Extractions



(ROBE & BRGM 2014)

Mesures constructives de protection de l'Air Ambiant contre les Gaz du Sol (FTOH, COHV, etc.) : SVE / Venting & Extraction sous Dalle



(ROBE & BRGM 2014)

Dans le cas des dépassements des CMA et en Prévention

→ I. Mesures constructives: Et.: Etanchéifications


Et. Fissures muraux


Et. des sols par béton spécial


Et. via des polyanes en PEHD, PE, etc.


Et. Par peintures étanches


Et. par Polymères


Et. latéraux par polyanes

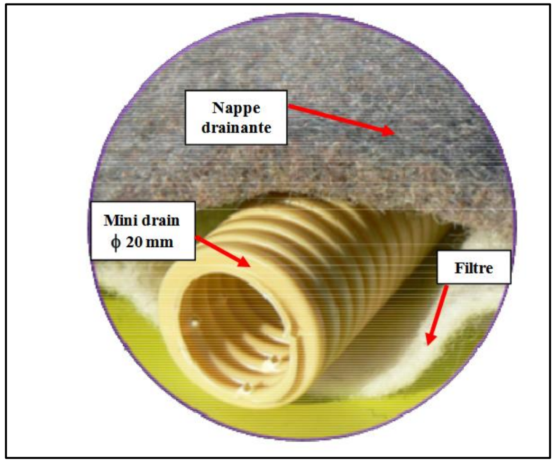

Et. Via Spraying

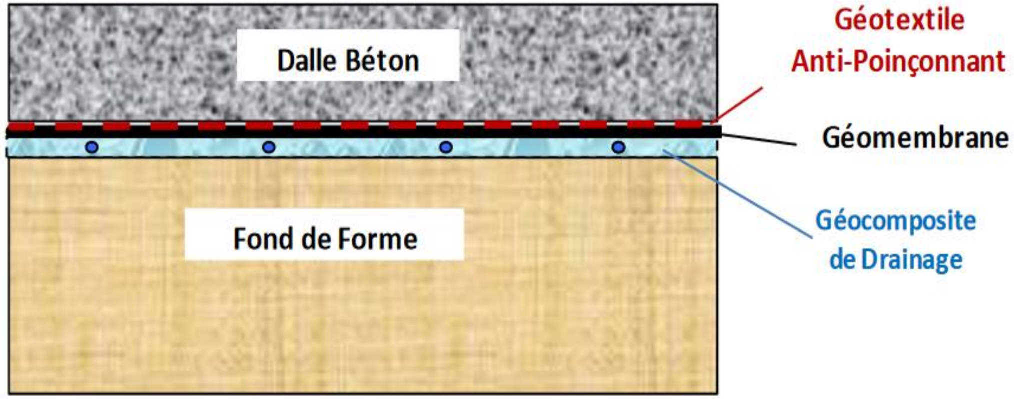

Et. des fondations

Dans le cas des dépassements des CMA et en Prévention

→ II. Mesures constructives: Drainages des Gaz

Drainages des Gaz sous Géotextiles

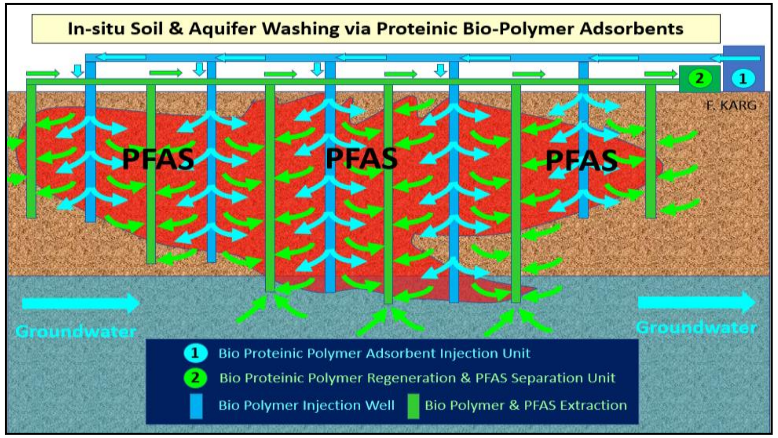




P. Gendrin et al. 2011

Conclusion:

- **Microbiological rehabilitation** is currently not possible.
- **Soil Remediation** includes Excavation and disposal or off-site incineration (expensive !), *in-situ or on-site Soil Washing*, Stabilization & Immobilization: Colloidal Carbon, Bio-Protein Polymers, etc.
- **Groundwater (GW):** the Remediation basic Technology is P&T (expensive !) with treatment by Granulated Activated Carbon (GAC) or other specifically adapted adsorbents (IX: ion exchange, specific absorbent resins, modified Clays, Bio-polymers), Foam Fractioning and in-situ Treatments by Injection of Colloidal Activated Carbon.
- **Surface Waters:** Algae-Bioaccumulation Traps.
- **In-situ applications for GW** are possible but need a technical-economic Feasibility Study.
- **Innovative R&D** Technologies like SonoLysis and special chemical oxidation (ISCO types) could be applied.



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Management of PFAS: Per- & Polyfluoro-Alkyl Substances:
Environmental Contaminations & Health Risk

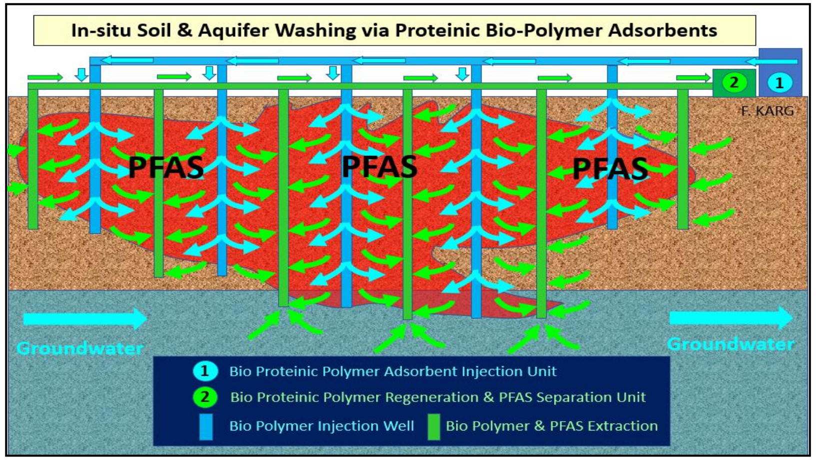
Thank You !

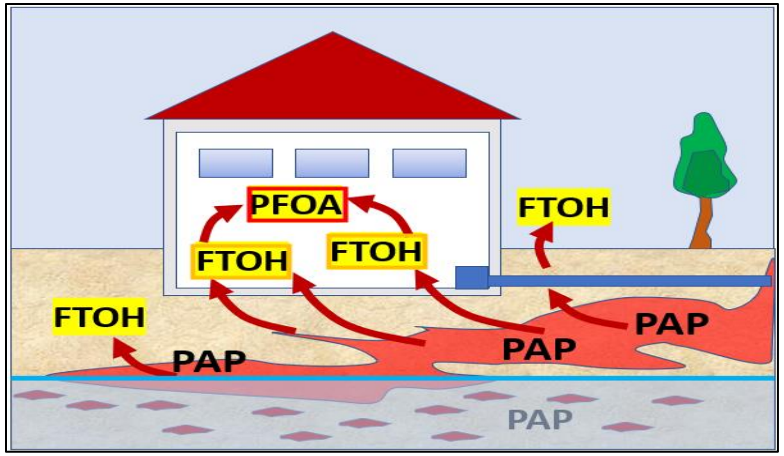
Questions? Remarks? Requests?

Dr. (PhD) Frank Karg / Scientific Director of HPC-Group (INOGEN JV) and

CEO-President of HPC INTERNATIONAL / France, Germany, Hungary, Balkan, etc.

Email: frank.karg@hpc-international.com / Phone: +33 607 346 916





INOGEN ALLIANCE