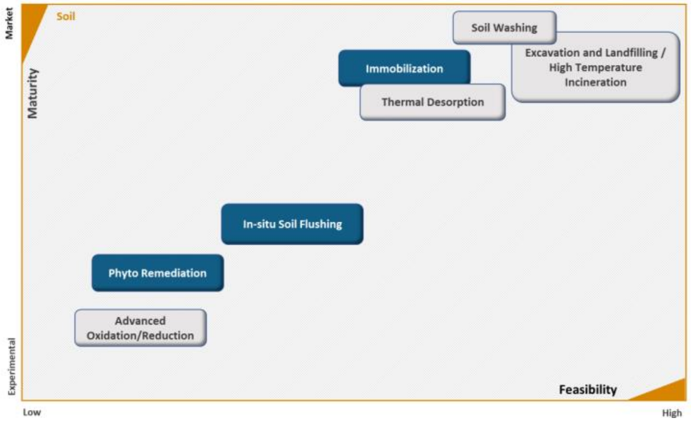
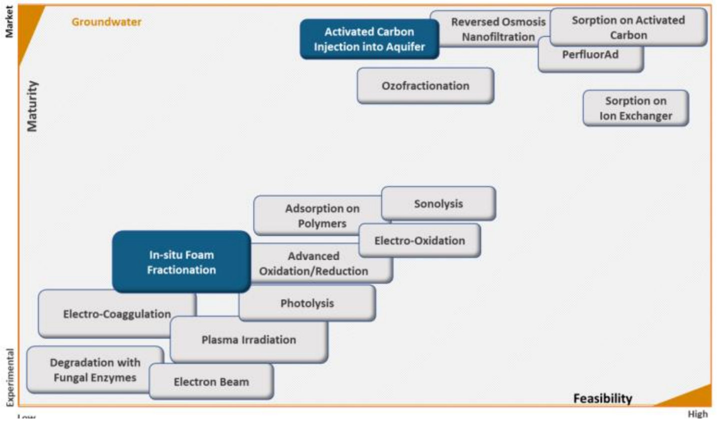
PFAS in soil - forever pollution, forever concern?
25 – 26 March 2025, Berlin

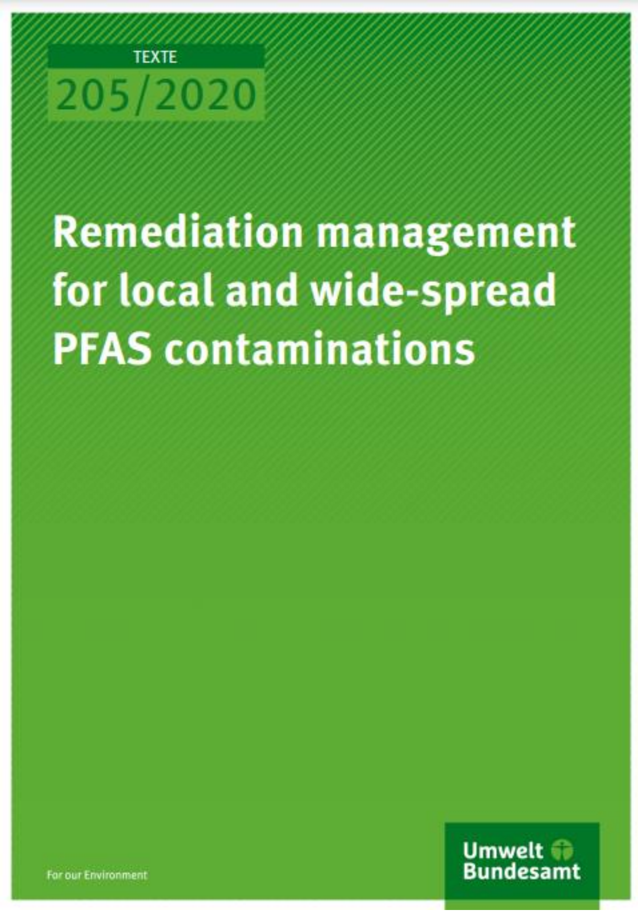
Remediation of PFAS in Soil and Groundwater: State of the Art.

Dr. Thomas Held
Arcadis Business Development Site Evaluation and Restoration | thomas.held@arcadis.com

Remediation Technologies – Soil and Groundwater







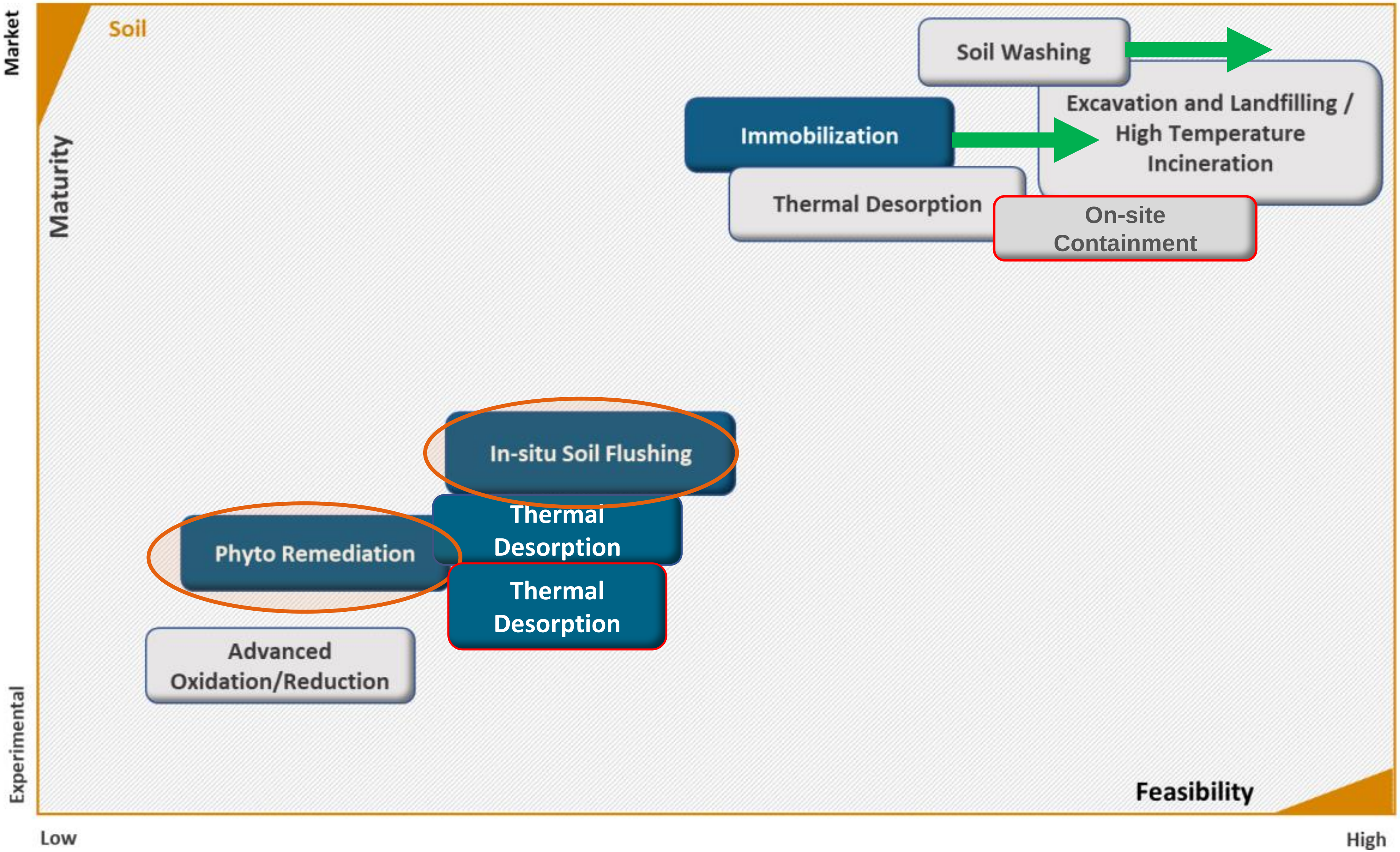
https://www.umweltbundesamt.de/publikationen/remediation-management-for-local-wide-spread-pfas

Remediation Technologies - Soil

Technologies for Soil Remediation

In situ applicable

Additional investigations



Technologies for Soil Remediation

- Immobilization & Landfilling: cost-efficient compared to landfilling alone
- In-situ immobilization: successfully tested in a 2½ year field trial (McDonough et al., 2021)
- Thermal desorption (in situ thermal treatment; ISTT): vaper extraction, cooling, GAC (pilot scale successful)*
- Phytoremediation: R&D confirmed what we already knew (low accumulation ratio, low efficiency for long-chain PFAS)

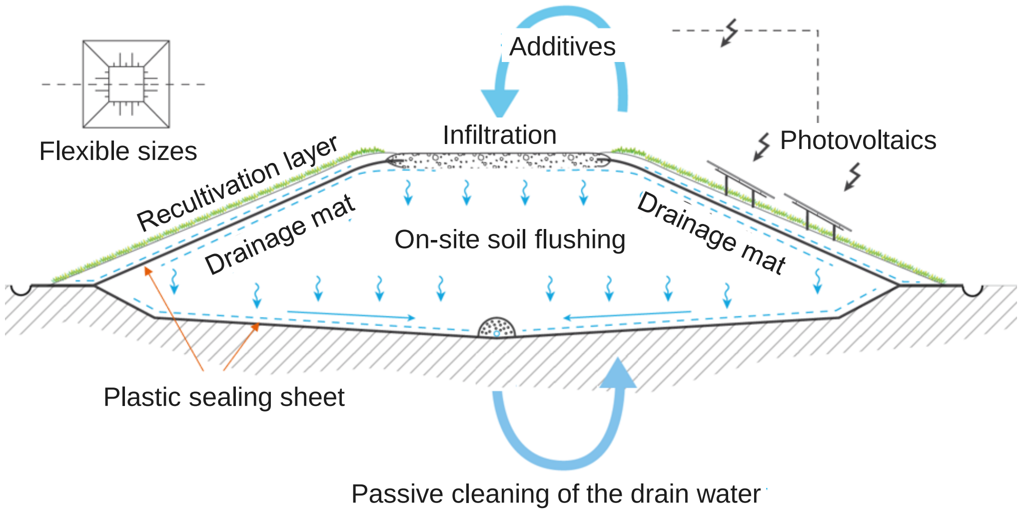
**) Ref: https://xcdacademy.s3.amazonaws.com/battelle/2024_Chlorinated/E3_1235_731_Fitzgerald.pdf*

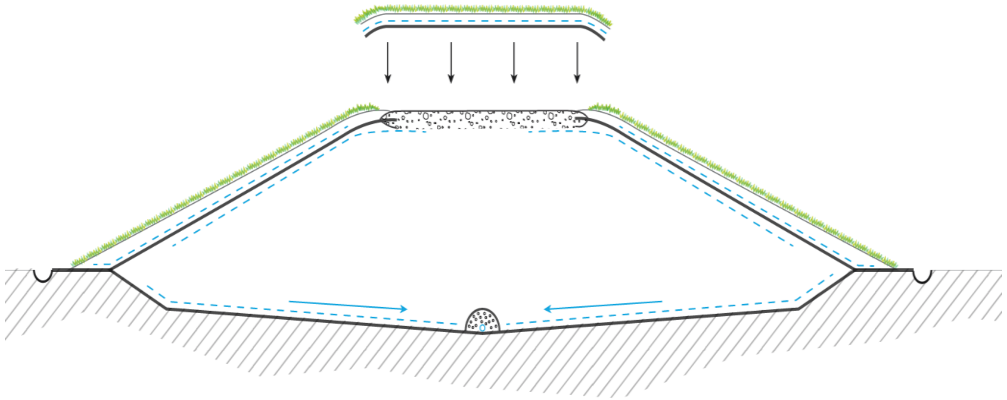
In-Situ Soil Flushing

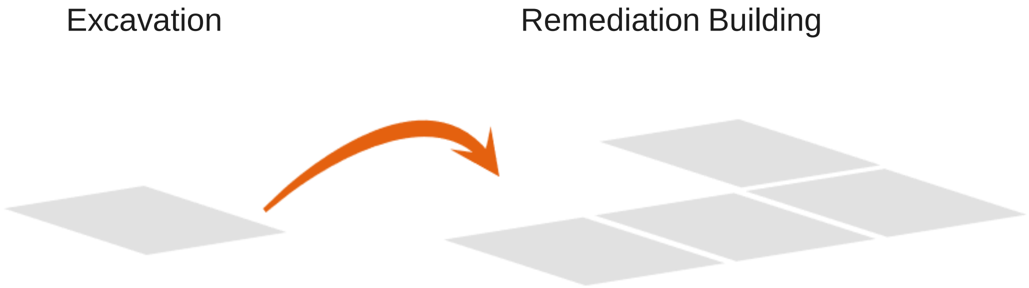
- Only feasible for well permeable soils
- Still many issues unresolved:
  - *Achievability of target values with reasonable effort*
  - *Uniformity of water saturation (→ Non-Newtonian Fluids*) (BRGM: ethanol/xanthan gum)*
  - *Leachability in the dependence of the PFAS fingerprint (precursor, cationic, non-ionic PFAS)*
  - *Additional benefits of added (proteinic) biopolymers (→ water treatment)*
  - *Economic efficiency compared to dig & dump*

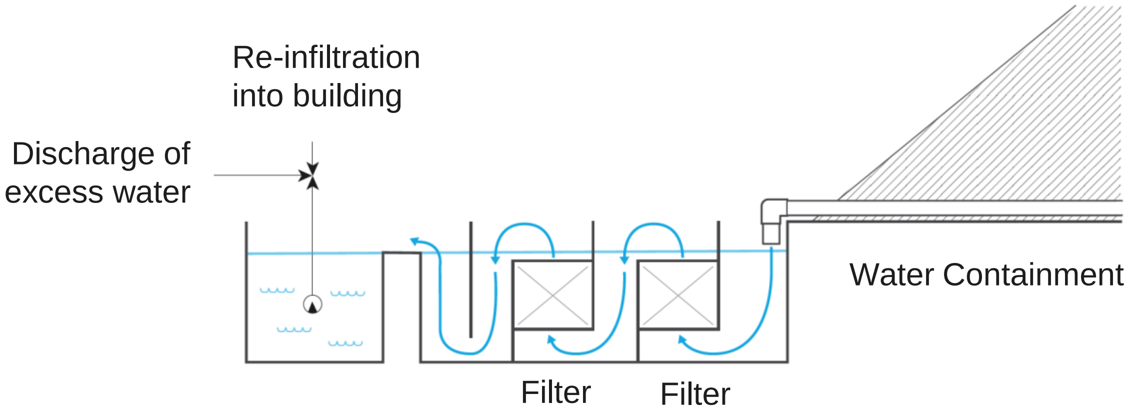
**NNF: viscosity changes depending on the acting shear forces. E.g. starch-water mixtures)

On-site Containment Multifunctional remediation building







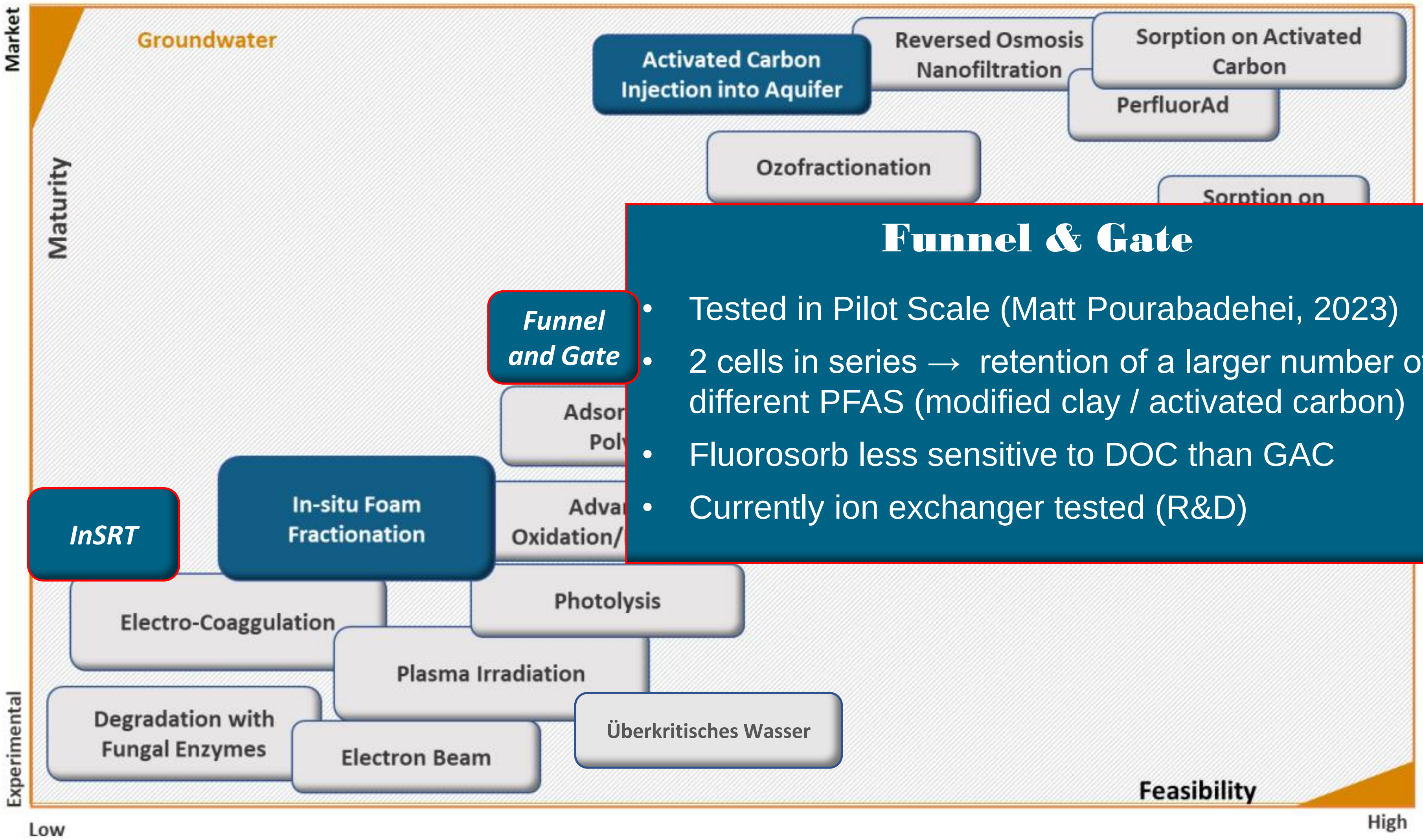


Remediation Technologies - Groundwater (in-situ)

Remediation Technologies for Groundwater

In-situTechnologies

In situ applicable



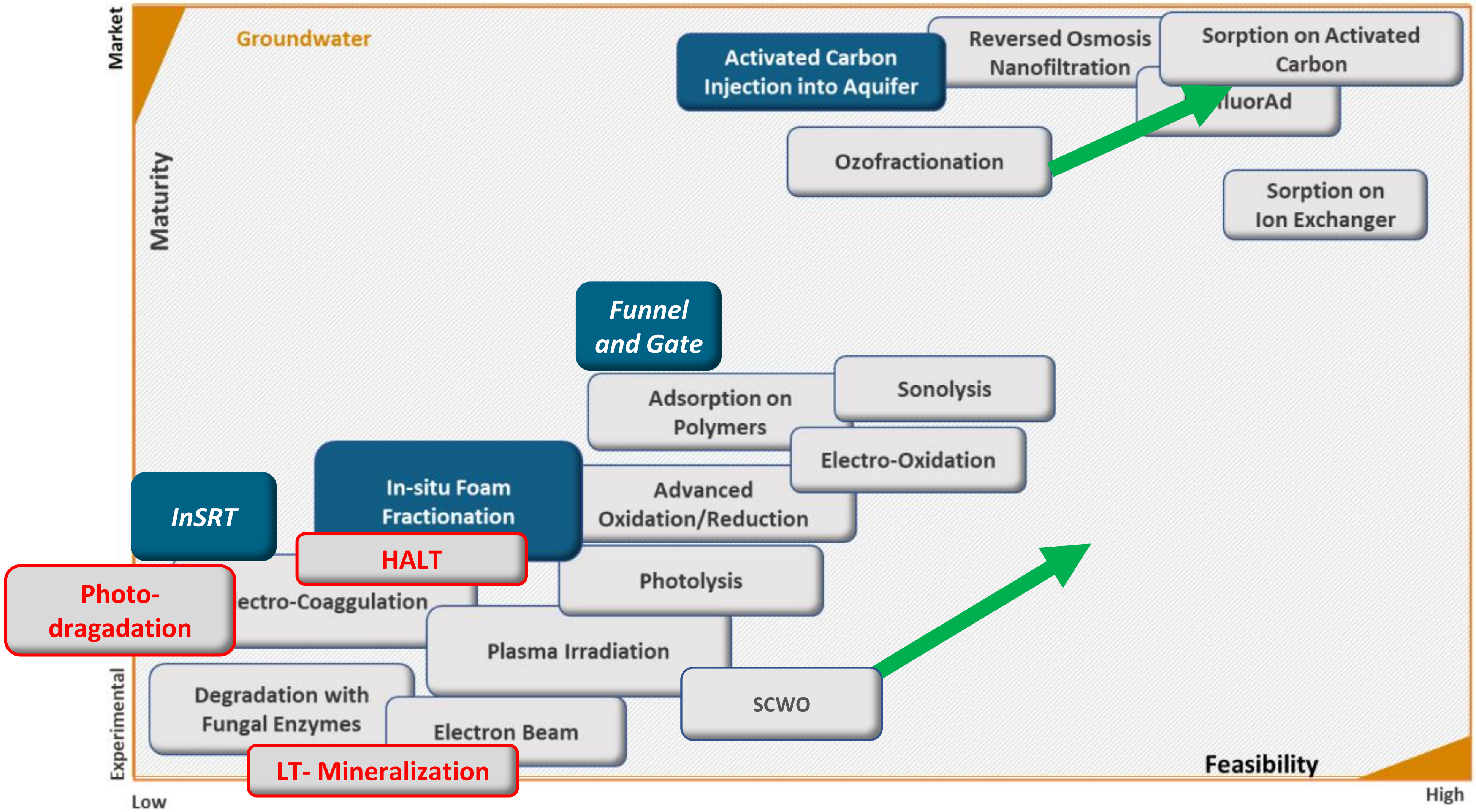
Funnel & Gate

- Tested in Pilot Scale (Matt Pourabadehei, 2023)
- 2 cells in series → retention of a larger number of different PFAS (modified clay / activated carbon)
- Fluorosorb less sensitive to DOC than GAC
- Currently ion exchanger tested (R&D)

InSRT
In situ reactor technology systems based on HRX wells

Remediation Technologies for Groundwater

based on P&T



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Ex-situ Groundwater Treatment

Closed F balance ?

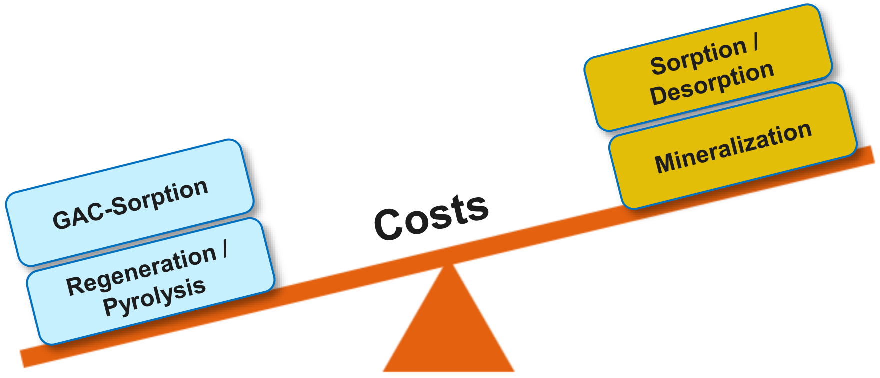
Technology	Environment	Degradation Efficiency	Pros /Cons	Source
Low Temperature Mineralization	DMSO/H_2O (8:1), NaOH, 120°C,	78 – 100 % degradation in 24 h	No degradation of PFSA	Trang et al., Science 377, 839–845 (2022)
Photodegradation	254 nm UV, 200 W Persulfat ($S_2O_8^{2-}$)	100 % PFOA-deg. in 4 h, PFOS poorly degraded		Verma, S., Next Materials 2 (2004) 100077
	UV/Sulfite/Iodide (20 mM SO_3^{2-}, 10 mM I^-, 10 mM HCO_3^-, 150 mM OH^-)	100 % defluorination: PFOS (60 min), PFOA (20 min), PFBS (240 min)		O'Connor, N., Science of the Total Environment 888 (2023) 164137
HALT(Hydrothermal Alkaline Treatment)	250 bar, 350 °C, < 5 M NaOH	PFOS in 30 min zu 100 % abgebaut, $PFAS_{gesamt}$ > 99,9 % Abbau	Solids also treatable	Gagliano, E. et al., Water Research 198, 2021, 117121
SCWO (Supercritical Water Oxidation)	> 374 °C, > 240 bar, O_2, Ca	$PFAS_{total}$ > 99,9 % degradation in 30 sec.	Solids also treatable, acid formation and corrosion	EPA/600/R-22/257 | September 2022

$$PFAS + O_2\,(air) \xrightarrow[>240\text{ bar}]{>374\,°C} H_2O + CO_2 + F^- + CaF_2 + heat$$

Ex-situ Groundwater Treatment

Interim Summary

- All (!) processes for the mineralization of PFAS require:
  - Harsh reaction conditions
  - High energy input
  - Mostly long treatment times
  - Expensive
- Unsuitable as a direct replacement for GAC sorption
- Concentrating up in small volumes (reversible sorption and desorption) required



Concentration Processes

PFAS Concentration Processes

Precursors & cationic PFAS considered ?

Technology	Process	Status	Pros /Cons	Source
Electro sorption and desorption	Anodic potential → sorption, Reversing polarity → desorption (concentrate formation)	Pilot scale	Conductive GAC required	Georgi u. Mackenzie 28. Jahrg. 2022/ Nr.2, 53-57
Desorption using microwaves	Generates > 600 °C → > 90 % PFAS removal, weight loss < 5 % (3 min)	Lab scale	Regeneration efficiency decreases with increasing number of cycles, no formation of short-chain PFAS	Gagliano et al., Water Res. 198, 2021, 117121
Hydrothermal treatment	200 - 260 °C, high pressure, aqueous suspension, 4 h → PFOA degradation > 99 %	Lab scale	No formation of short-chain compounds .PFOS requires harsher reaction conditions (260 °C, 16 h)	
Regenerable magnetic anion ion exchangers (MIEX)	electrostatic sorption dominating over hydrophobic interactions	Piot Scale	Fast (< 30 sec,) low efficiency for short chain PFAS, MeOH/salt for MIEX regen.	Tan, X. et al., Angew. Chem. Int. Ed. 2022, 61, e202213071
Foam fractionation	Injection of air in a water column	Full scale	Low efficiency for short chain PFAS	

Take Home Message

- Soil washing and immobilization (optional: in-situ) are becoming more and more established
- There are several processes available for the mineralization of PFAS in aqueous concentrates
- Bottleneck is still the concentration step
- New focus on in-situ barrier processes (especially sorption in funnel-and-gate systems)
- More R&D required in cost effective concentration processes
- **Economic feasibility studies are almost always missing**

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