PFAS Remediation - what are the problems and which technologies are appropriate?

- a practical perspective

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Why is PFAS remediation problematic

1. Many substances, most unknown → remedial targets uncertain
2. Environmental fate not well known and probably highly variable
3. Effectiveness of source zone vs. plume treatment unknown
4. Unfavorable properties → many remedial techniques unsuitable

Remedial Targets Uncertain

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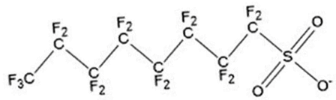
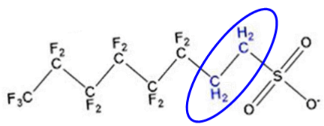
Thousand PFAS may occur at a contaminated site

Many transformed from polyflourinated to perflourinated via complicated degradation patterns

PFOS  → Perfluorinated

6:2 FTS  → Polyflourinated

What is the remedial target?

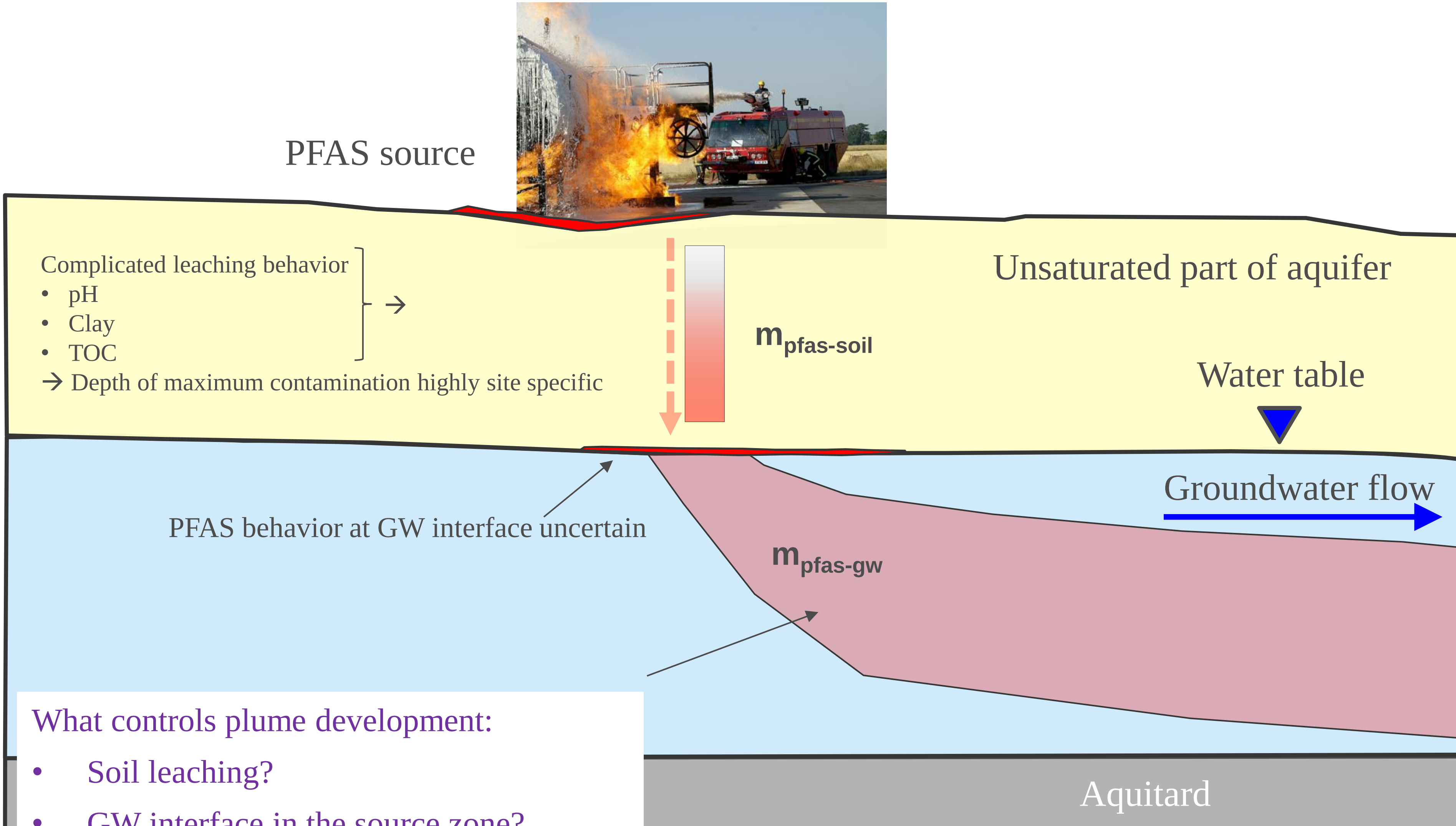
- *PFOS and PFOA?*
- *PFAS 11? (drinking water)*
- *PFAS 22?*
- *100 perflourinated? – most persistent*
- *1000 polyflourinated?– less persistent*
- *“All” PFAS*
  - ***TOF*** *(Total Oxidizable Precursors)*
  - ***EOF*** *(Extractable Organo Fluorine*
  - ***AOF*** *(Adsorbable Organic Fluoride)*

Has to be determined for each project

Already an issue when evaluating Pilot studies

Definitely and issue for full scale remediation starting in 2017

Fate - source zone vs plume treatment



What controls plume development:

- Soil leaching?
- GW interface in the source zone?
- Mass adsorbed in saturated zone?

→ <u>**how efficient is source zone treatment?**</u>

Fate - source zone vs plume treatment

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Mass balance indicates that source zone treatment is more efficient than pump and treat

	Amount in source zone, saturated and unsaturated soil (Kg PFAS)	Down-gradient transport to risk receptor (g PFAS /year)	No of years before source zone is depleted = pump and treat years	Transport media
Site 1	20 - 80	500	40 - 140	Surface water in peat area
Site 2	1-3	5	200 - 600	Groundwater
Site 3	6-11	40	150 - 275	Groundwater + surface water
Site 4			200 - 500	Groundwater + surface water

Probably underestimated mass in source zone compared to groundwater:

- Based on analyzed PFAS: $m_{pfas\text{-}soil} > m_{pfas\text{-}gw}$
- If 1000s of (unknown) PFAS in soil act as a plume source : $m_{pfas\text{-}soil} >>> m_{pfas\text{-}gw}$

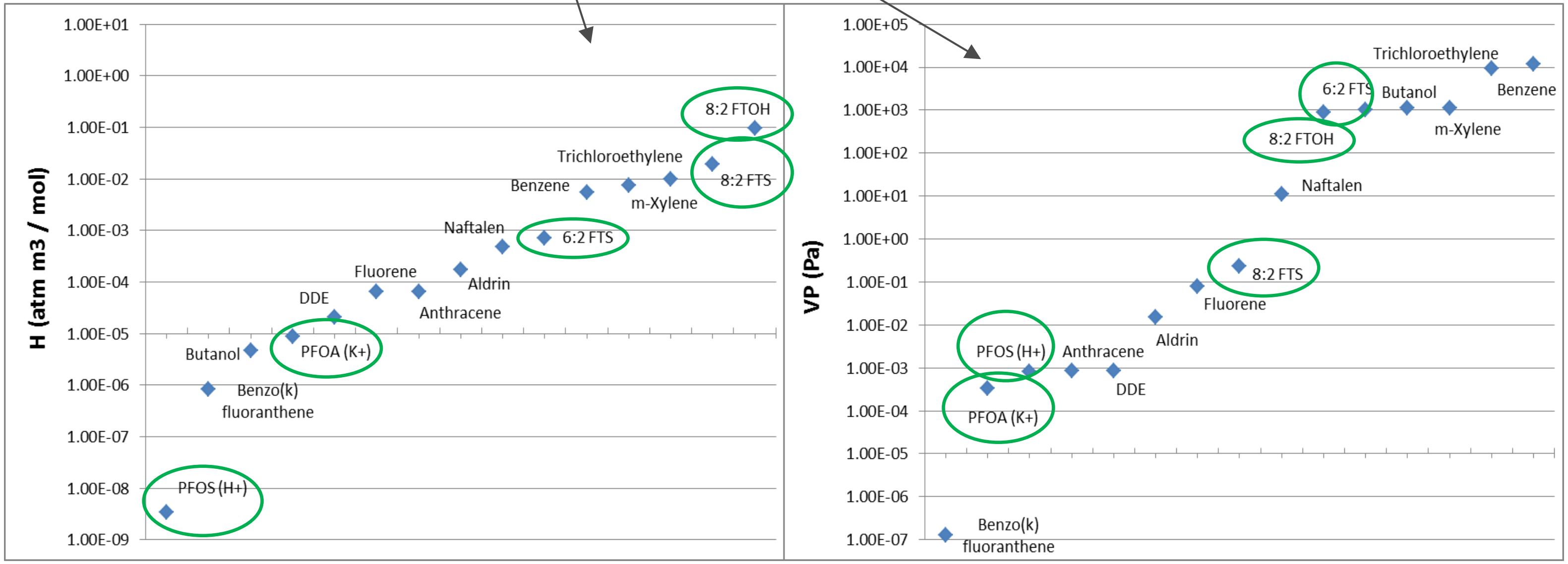
→

→ Source zone depletion/pump and treat may require even more time

Important PFAS properties for treatment options – *persistence, volatility and solubility*

- Some PFAS (e.g. perflourinated) are highly persistent, do not biodegrade and has a very long or indefinite hydrolysis and photolysis half life
- Many PFAS (e.g. polyflourinated) are less persistent but will mostly degrade to form perflourinated dead end-products

- High water solubility, low Koc of critical PFAS (?) → groundwater problem
- Generally low volatility of critical PFAS



Excavation

Established approach for source zones

Unsaturated zone + upper part of saturated

Costly

Transfer the problem to different site (no risk reduction?)

External landfill of excavated soil

- Traditional treatment of waste leachate not suitable for PFAS
- Outgoing PFAS leachate levels >> levels within facility
- General reluctance in Sweden to receive PFAS contaminated soil
- PFAS in leachate part of compliance conditions in Sweden
- Swedish Waste Management Association has retained Sweco to investigate this issue
- Degree to which PFAS contaminated soil can be externally landfilled in Sweden is unknown

Excavation

Soil washing of excavated soil

- Proven technology for PFAS
- Two pilot studies in Sweden (with Sweco), one full scale remediation (20 000 tons) will start in Mars
- Not suitable for silty/clayey soil
- Water and sludge fractions needs to be treated

Full containment/capping of excavated soil

- Requires space/volume.
- Costly
- Permanent?
- One known PFAS project - Guernsey

Stabilization of excavated soil

- Pilot scale projects indicates suitability for PFAS. Several products on the market.
- Long term stabilization/adsorption not reported

Incineration

- 900 – 1100 C
- Very costly

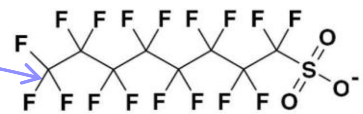
In Situ Chemical Oxidation

Strong oxidant added directly to contaminated matrix (i.e. injection)

Both source zone and plume

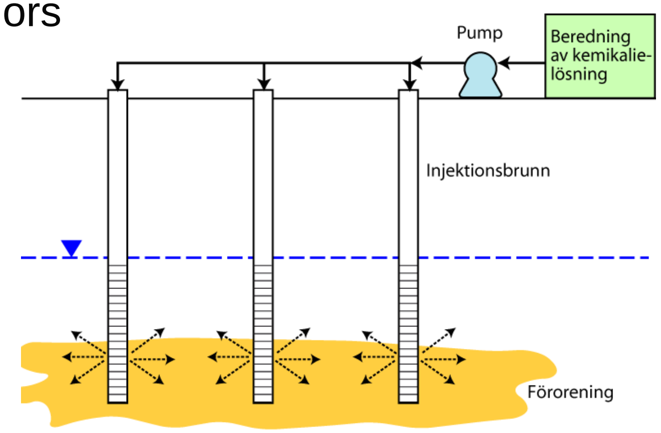
Generally established technology, several suppliers

In situ oxidation and *ex situ* treatment of extracted water (pump and treat) can be co-installed



Applicability PFAS

- C-F bond extremely stable requires oxidation potential > 2.9 – 3 eV
→ traditional advanced oxidation technologies has to be further developed
- Several approaches currently evaluated by different vendors
- Pilot studies have been initiated
- Perozone[tm] , Perozox[tm], ScisoR[tm] etc.....
- What are the oxidation products in a source zone when 1000s of PFAS are being treated?



Pump and treat

Established technology

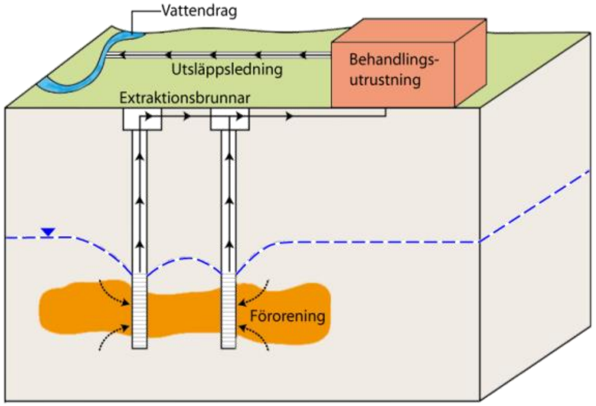
Sparsely used for CAH/DNAPL etc. for god reasons – rebound and mass transfer rates

Low initial investment, often high total cost due to long treatment times (mass balance problem)

Generally viewed as a containment approach rather than a full remediation

Active carbon filter to treat extracted water

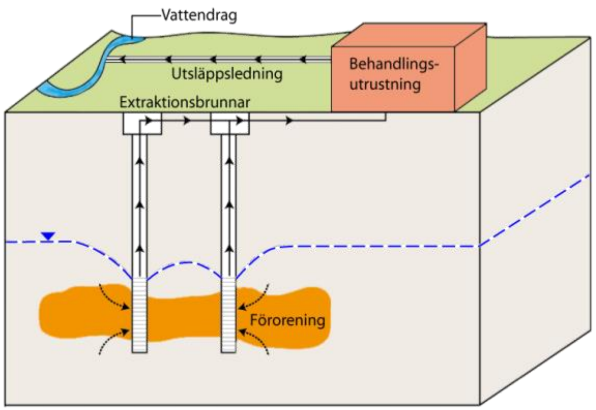
- May function, but GAC 20 – 100 lower sorption for PFAS compared to e.g. BTEX
- GAC increasingly less effective as PFAS chain length decreases
- Variable treatment efficiency: PFBA<PFHxA<PFOA<PFOS<PFHxS
- Groundwater quality at many sites with DOC, Fe/Mn requires sandfilter pre-treatment and increased running cost and lower treatment efficiency
- Common with fast break-through of PFAS → increased monitoring frequency and regeneration frequency → increased cost



Pump and treat

Other methods for treating extracted water

- New filter materials (clay-organic, resins, zeolite etc..)
- Membrane technologies (nano + reverse osmosis) will function, but high investment and running cost especially for a field treatment system
- Anion exchange will function but uncertain efficiency for some PFAS
- PFAS precipitation agents will function. At least one supplier.
- Bio reactor will not function (does not biodegrade)
- Advanced oxidation methods (AOPs) will work, and field scale equipment may be cost effective
  - peroxide, temperature, nano-ozone etc.
  - several suppliers/brands
  - varying levels of confirmed field scale functionality



Immobilization/stabilization

Addition of a sorbent immobilizes PFAS in source zone or plume

In soil → decreased leaching

In plume → contains plume development

Potentially cost effective

Common issue the long term viability

Applicability PFAS

- Mass balance of PFAS sites may favor this approach since the PFAS mass that needs to be immobilized/retarded is low
- GAC + Enzyme + $CaCO_2$ has been tested as a barrier material where PFAS is "permanently" humified → promising lab results
- GAC specifically developed for plume injection has been tested. Variable efficiency for different PFAS
- Two commercial products available for soil source zone immobilization via PFAS adsorption. Medium term leachability of PFAS proven to be highly reduced (but not long term).
- PFAS precipitation agent is to be tested in soil matrix during 2017. Promising lab results.

Long term viability? PFAS does not biodegrade/mineralize to non harmful end-products which requires very strong and long-term stability of PFAS immobilization

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Other methods

Electrochemical degradation/oxidation

Promising lab results for PFAS in complex soil and GW matrix. Pilot test during 2016 – 2017.

Phyroremediation

Pilot scale test in Sweden. Different tree species tested. Uptake proven, mass balance needs to be evaluated. Likely to be a polishing method.

Thermal methods

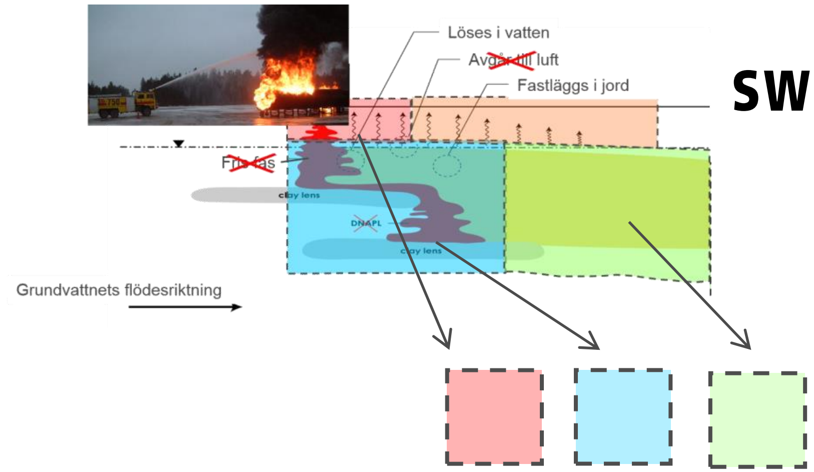
Thermally enhanced SVE to be tested in Sweden during 2017 – 2018

SWECO will initiate a treatment train pilot study during 2017 together with clients.

Will attempt to answer the question regarding how fast a source zone treatment can stop a plume from spreading

Summary

Applicability of remedial approaches



Excavation	**Yes/No** – 1) PFAS treatment in waste leachate at landfills problematic 2) waste treatment facilities unwilling to receive contaminated soil	✓	✓	
Pump and treat	**Yes** - 50 to X*100 years of treatment time. GAC challenging		✓	✓
Pore gas extraction/air injection	**No** → not volatile			
In situ soil flushing	**Yes**, related to pump and treat		✓	
Soil washing	**Yes**, not all soil types	✓	✓	
Thermal treatment	**Possible**, no lab or pilot scale studies	(✓)	(✓)	
Biological in situ treatment	**No** → not biodegradable			
Advanced ISCO	**Yes, probably,** lab studies successful, pilot studies are commencing	(✓)	✓	✓
Phytoremediation	**Efficiency?, pilot studies are commencing**	(✓)	(✓)	✓
MNA	**No** → not biodegradable			
Immobilization	**Yes, probably**, technologies based on immobilization/sorption are being tested	✓	✓	✓