

Technologies for treating PFAS contaminated water:

analysis based on our own experience,
Including an economic assessment

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Water treatment plant in Switzerland

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Züblin Umwelttechnik GmbH

HQ in Stuttgart / Germany

- One of the leading European technology companies for the remediation of contaminated sites and treatment of construction water
- Over 40 years of experience and more than 500 active projects national and international
- 200 employees
- Wide range of site-specific remediation methods
- Since 2009, increasing number of projects to clean water contaminated with PFAS
- We develop individual solutions for our customers
- International experience worldwide



Headquarter of Züblin Umwelttechnik GmbH, Markgröningen, Germany

Range of services – Departments

Brown-field remediation

- Pump & Treat
- In-situ thermal remediation
- Biological treatment processes
- Soil vapour extraction



Construction & Tunnel Water

- Modular water treatment plants
- Sludge treatment systems
- Dewatering of construction pits
- Trouble shooting in short notice



Dismantling & Disposal

- Special Projects
- Big scale soil washing plants
- Disposal
- Ventilation of excavation pits/halls



Plant construction

- Design, planning, construction,
- Electrical and M&C Technology
- Installation, service, operation
- Spare parts service



Brown-field remediation – applied processes

Pump & treat / in-situ processes

- Removal of contaminants by desorption and/or adsorption
- In-situ biological degradation
- In-situ chemical oxidation/reduction
- Soil vapour extraction
- Removal of metals



In-situ thermal remediation

- ISTR with electric heating elements (HE) in a full-scale project in Spain:
 - 1,000 KW installed HE capacity, power up to 2 kW / meter HE
 - Reached temperatures up to 400°C
 - Extraction & conditioning of hot vapours, loaded with pollutant
- Groundwater extraction with DPE



Soil treatment processes

- Soil washing plants for PFAS/TPH
 - full-scale up to 2,000 tons/day
 - mobile plant up to 200 tons/day
- Biological soil treatment
- Ventilation of excavation pits / halls



Treatment of PFAS contaminated water – selected references

Project	Medium	Process	Time	Capacity
CH-Solothurn	Landfill leachate	Pretreatment, GAC	since 2026	bis 4 m ³ /h
I-Como	Drinking water	GAC, IAT	since 2025	0,2 m ³ /h
D-Erfstadt, Energy supplier	Ground water	GAC	2025	50 m ³ /h
B-Belgien, Pilot project	Ground water	Pretreatment, GAC, IAT	since 2025	bis 6 m ³ /h
D-North Germany, Airport	Sprinkler systems – Water	GAC	2024	m ³ /h
D-Ansbach, Military site	Ground water	BF, GAC, IAT	since 2024	1,5 m ³ /h
D-Hechingen, Industry	Sprinkler systems - Water	GAC	2023	4 m ³ /h
D-Augsburg, Pilot project	Landfill leachate	Foam fractioning, GAC	2023	1,5 m ³ /h
CH-Collombey, former Refinery	Ground water	GAC, 5 treatment lines	since 2023	180 m ³ /h
D-Düsseldorf, Chem. Industry	Ground water	SF, GAC	since 2023	150 m ³ /h
D-Wittmundhafen, Military site (Airport)	Soil, process water	Pretreatment, GAC	since 2022	200 m ³ /h
D-Berlin, Water protection area	Ground water	SF, GAC	since 2022	150 m ³ /h
D- Rheinmünster, farmland	Ground water, Irrigation	Pretreatment, GAC	since 2022	m ³ /h
D-Coburg, Pilot project	Landfill leachate	GAC	2022	1-2 m ³ /h
CH-Wallis, Chem. Industry	Ground water	GAC	since 2022	50 m ³ /h
D-Bremen, Airport	Ground water	SF, GAC	since 2022	14 m ³ /h
D-Röthenbach, Industry	Ground water	GAC	since 2021	50 m ³ /h
D-Sinzheim, Sport stadium	Ground water, Irrigation	GAC	since 2021	8 m ³ /h
I-Spinetta, Chem. Industry	Ground water	GAC	since 2020	40m ³ /h
D-Nuremberg, Airport	Ground water	Foam fractioning, GAC	since 2020	25 m ³ /h
D/BW, Car producer	Ground water	GAC	since 2020	30 m ³ /h
D-Bavaria, Industrial laundry (Fire fighter cloths)	Process water	GAC	since 2009	1 m ³ /h

Our PFAS purification systems

- efficient and economical
- since 2009 over 80 systems in Germany, France, Italy and Switzerland



Mobile plants: PFAS COMPACT



Soil washing, process water



Stuttgart Airport, groundwater



Airport, process water from soil washing



Sprinkler system, extinguishing water



Drinking Water Protected Area, Groundwater



Agriculture, Groundwater



Firefighter clothing, laundry

Practice-relevant cleaning methods



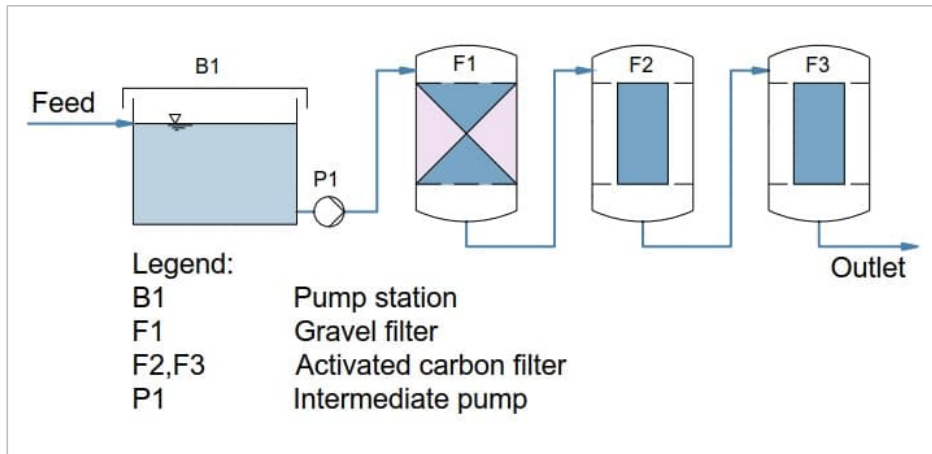
Treatment methods

- **Activated carbon adsorption**
- **Ion exchange**
- **Foam fractionation**
- Membrane separation
- Various adsorbents (zeolites, clay minerals)

Aqueous media

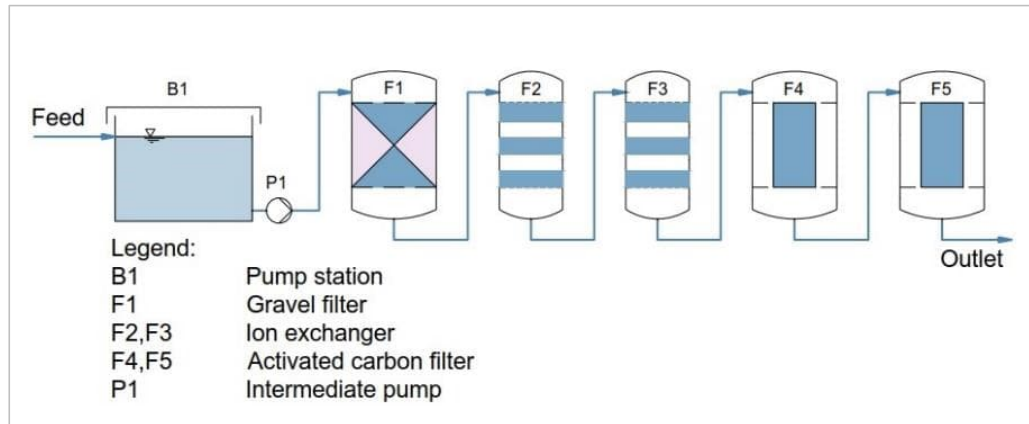
- Groundwater
- Leachate
- Extinguishing water
- Process water (e.g. from soil washing)

Adsorption to granulated activated carbon (GAC)



- Pressure filters, multi-stage
 - Gravel filter for pre-treatment
 - Two stage GAC filters
- Granulated activated carbon
 - Slow diffusion kinetic → **contact time ~30 minutes**
 - **PFAS optima®** (own brand of Züblin UT), reactivatable), cost, depending on quantity, **~3 € / kg = 1.4 € per Liter**
- PFAS loading 0.01 - 0.1 wt. %, mainly depending on:
 - PFAS spectrum
 - DOC
 - purification target
 - Activated carbon (type bituminous coal)
 - Regeneration possible
- Filtrate quality < 10 ng/l per individual compound

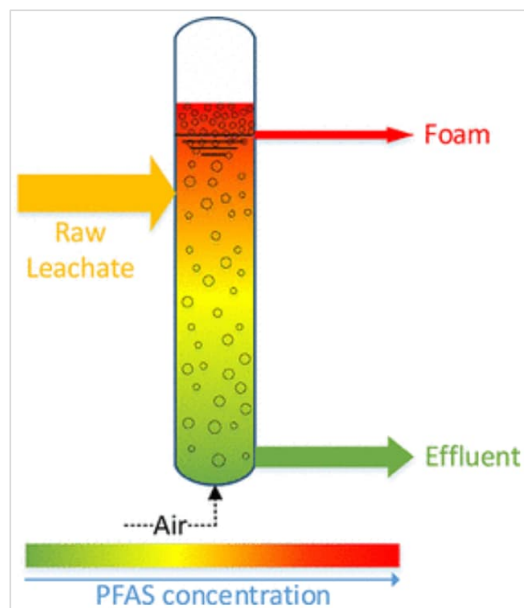
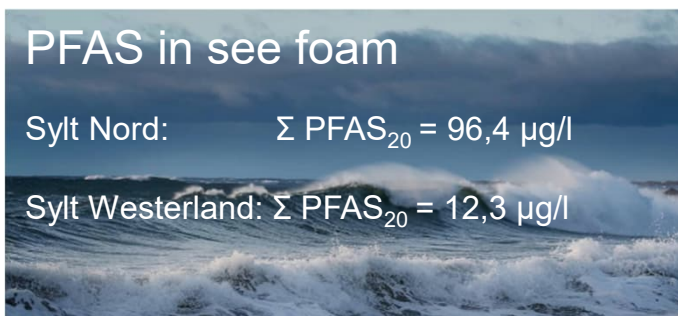
Removal of PFAS with ion exchange resins (IEX)



- IEX filters as part of a treatment train:
 - Gravel filter for pre-treatment
 - IEX anion exchange resin filters
 - GAX filters for adsorption and final cleaning
- Ion Exchange resins, **cost ~15 € / Liter**
 - High functional density and fast kinetic
→ **low contact time of ~4 minutes**
 - Long delivery time up to 6 months

- PFAS loading 0.5 - 0.9 wt. %, mainly depending on:
 - PFAS spectrum
 - Presence and concentration of impurities (Anions & DOC [ppm] >>> PFAS [ppb], others)
 - purification target
 - Resin type (after use partially regeneration or incineration)
- Filtrate quality < 1 ng/l (!) per individual compound possible
→ **as well for short-chain PFAS** (e.g. PFBA)

Foam fractionation (FF)



Foam Fractionation

- First patent in 1918, Wilhelm Ostwald (Nobel Laureate, DE)
- Adsorption of surface-active compounds on the hydrophobic surface of **gas bubbles**
- Separation of foam

Application

- Biotechnology, protein separation
- Fish farming
- PFAS removal (PFT: perfluorinated surfactants)

Efficiency

- Efficient for **long-chain PFAS and high concentrations**
- For short chain PFAS addition of surfactants required
- Generation of foam is different case by case
- Combination with adsorption with GAC and/or IEX
- Final disposal of highly concentrated foam by incineration

Laboratory / field scale pilot tests – R&D activities



Innovation and process optimization for PFAS removal

- Soil flushing
- Foam fractionation with sludge from soil washing
- Performance testing of new adsorbent materials

Recent scientific works together with Universities

- Chwalek C (2022); Master thesis, University a. Sc. Reutlingen/Züblin
- Hermann T (2023); Bachelor thesis, University Esslingen/Züblin
- Rösner S (2024); Bachelor thesis, University a. Sc. Heilbronn/Züblin
- Mayer J-E (2025); Master thesis Univ. Esslingen/Züblin

Case study Germany – GAC adsorption with PFAS optima®



Remediation measure

- Treatment of groundwater, drinking water source

Contaminants

- PFAS (mainly PFOS, PFHxS)

Flow rate

- 125 - 150 m³/h

Treatment train

- (1) Pre-treatment Fe/Mn-removal, aeration & filtration
 - (2) Adsorption of DOC with GAC
 - (3) Adsorption of PFAS with GAC, 2 stages á 3 filters
 - (4) Sludge treatment
- Since 07/2026: test phase 2 m³/h IEX for removal of PFAS after (2)

Operation period (Status 09/2026)

- since 11/2022 (47 months)
- Treated water quantity: 3,650,000 m³ (cost ~0.40 € / m³)

Discharge values

- Freight Σ PFAS₂₀ / year ~3,700 g removed
- PFOS, PFHxS & PFOA: ≤ 0.001 µg/l

Case study Airport Nuremberg – GAC adsorption



Remediation measure

- Hydraulic barrier downstream

Contaminants

- PFAS (mainly PFOS, PFHxS)

Flow rate

- ca. 20 m³/h

Treatment process

- (1) Activated carbon (GAC) adsorption (2x 15 m³)
- (2) Test phase with foam fractionation in lab and field scale, continuous mode. Result was relation foam/m³ to disposal about 10 Vol-%.

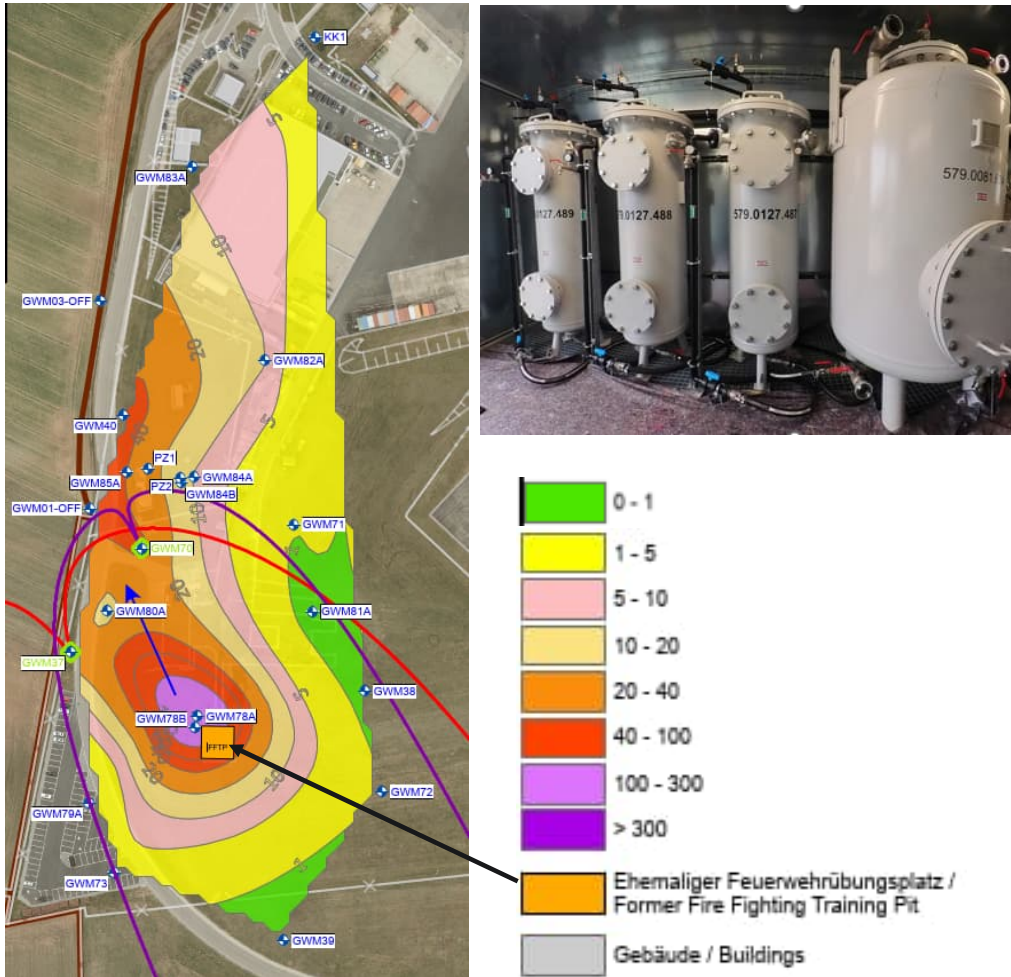
Operation period (Status 01.10.2026)

- since 09/2020 (72 months)
- AC change 4 x filters (1 x 15 m³)
- Treated water quantity: ~600,000 m³ (cost ~0.90 € / m³)

Discharge values (cleaning performance)

- Freight $\sum$ PFAS₁₃ / year ~1,000 g removed
- PFOS: $\leq 0.02 \mu\text{g/l}$ ($\leq 0.01 \mu\text{g/l}$)

Case study military Airport – Bavaria



Remediation measure

- Hydraulic barrier downstream

Contaminants

- PFAS (mainly PFOS, PFHxS > H4PFOS > PFHxA)

Flow rate

- ~1.5 m³/h

Treatment process

- Activated carbon (GAC) adsorption (1x 1 m³)
- Ion exchange resin (IAT, 3x 0.2 m³)

Operation period (Status 01.10.2026)

- since 10/2024 (24 months)
- GAC: use of 1 filter á 1 m³ (still first filling in use)
- IEX: use of 9 filter á 0.15 m³ (first filling, changes)
- Temporarily: 3 filter with clay material á 0.15 m³

Discharge values (cleaning performance)

- $\sum \text{PFAS}_{13}$: $\leq 0.2 \mu\text{g/l}$ ($\leq 0.01 \mu\text{g/l}$)
- PFOS: $\leq 0.02 \mu\text{g/l}$ ($\leq 0.01 \mu\text{g/l}$)

Economic assessment for PFAS groundwater treatment ^{1, 2}

Analysis based on our own experience with realized groundwater treatment projects, 2018

ZÜBLIN Umwelttechnik GmbH has >15 years of experience realizing projects to remove PFAS from groundwater. Cost comparisons were done for several realized projects, distinguishing between non-recurring costs (well equipment, assembly, commissioning of the treatment plant, repairs) as well as specific costs per treated cubic meter (OPEX).

Excerpt of publication 2018, based on model calculation for flow rate of 25 m³/h and two PFAS concentrations

Tab. 3: Cost comparison (without VAT) of PFAS purification processes for a flow rate of 25 m³/h with a concentration of Σ PFAS = 10 µg/L in the feed

Purification process	Activated carbon adsorption	Ion exchange	Flocculation	Membrane process
Non-recurring costs	24000 €	28000 €	33000 €	47000 €
Materials	0.07 €/m ³	0.17 €/m ³	0.15 €/m ³	0.63 €/m ³
Total OPEX	0.50 €/m ³	0.79 €/m ³	0.82 €/m ³	1.87 €/m ³

Tab. 4: Cost comparison (without VAT) of PFAS purification processes for a flow rate of 25 m³/h with a concentration of Σ PFAS = 50 µg/L in the feed

Purification process	Activated carbon adsorption	Ion exchange	Flocculation	Membrane process
Non-recurring costs	24000 €	28000 €	33000 €	47000 €
Materials	0.28 €/m ³	0.71 €/m ³	0.32 €/m ³	0.80 €/m ³
Total OPEX	0.72 €/m ³	1.34 €/m ³	1.04 €/m ³	2.09 €/m ³

Following these economic assessment will be shown for the case of the military Airport in Bavaria.

1: Edel H-G, Grünhagen D, Kellner C. (March 2018); English translation from "Handbuch Altlastensanierung und Flächenmanagement (HDA):

PFAS Groundwater remediation: State of the art technology and comparison of costs

2: Edel H-G, Korte D, Kellner C., Rehning U (2015); English translation from "Korrespondenz Wasserwirtschaft", 550-554, DWA e.V.: PFC-Grundwassersanierungen – Technologie und Kosten aus über fünf Jahren Praxiserfahrung

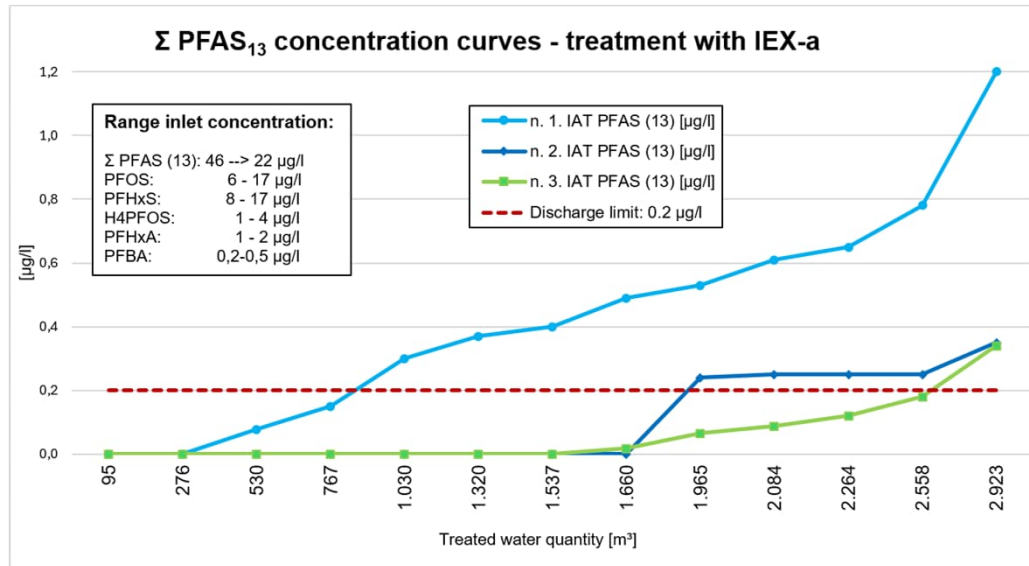
Economic assessment military Airport Bavaria

Sum of 13 relevant PFAS (monitoring during operation period 10/2024 – 09/2026)

Abbr.	Parameter	Structure	Type *	Unit	Concentration		
					Min	Max	Average
PFOS	Perfluorooctane sulfonic acid	$C_8HF_{17}O_3S$	LC	ng/l	520	38.000	6.916
PFHxS	Perfluorohexansulfonic acid	$C_6HF_{13}O_3S$	SC	ng/l	270	17.000	6.745
H4PFOS	1H,1H,2H,2H-PerfluorooctylSulfonsäure	$C_8H_5F_{13}O_3S$	LC	ng/l	0	3.700	1.451
PFHxA	Perfluorohexanoic acid	$C_6HF_{11}O_2$	SC	ng/l	130	2.300	1.101
PFPeA	Perfluoropentane acid	$C_5HF_9O_2$	SC	ng/l	160	1.500	689
PFOA	Perfluorooctanoic acid	$C_8HF_{15}O_2$	LC	ng/l	43	1.200	522
PFHpS	Perfluoroheptane sulfonic acid	$C_7HF_{13}O_3S$	SC	ng/l	11	1.100	433
PFBS	Perfluorobutane sulfonic acid	$C_4HF_9O_3S$	SC	ng/l	16	890	430
PFNA	Perfluorononanoic acid	$C_9HF_{17}O_2$	LC	ng/l	20	720	373
PFBA	Perfluorobutane acid	$C_4HF_7O_2$	SC	ng/l	37	470	230
PFDA	Perfluorodecanoic acid	$C_{10}HF_{19}O_2$	LC	ng/l	0	41	1
PFOSA	Perfluorooctane sulfonamide	$C_8HF_{17}O_3S$	LC	ng/l	0	12	0
PFHpA	Perfluoroheptane acid	$C_7HF_{13}O_2$	LC	ng/l	44	570	273
	Σ 13 PFAS			ng/l	1.251	67.503	19.164

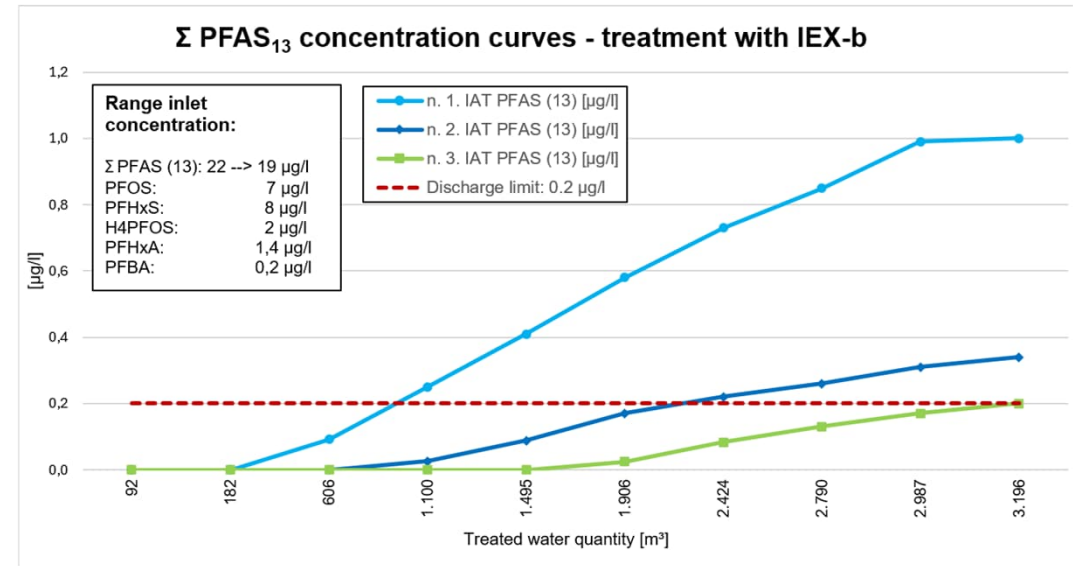
* Types of per- and polyfluoroalkyl substances (PFAS): USC = ultra-short-chain ($C1 - C3$), SC = short-chain ($C4 \leq C7$), LC = long-chain ($\geq C7$)

IEX type a and b (10/2024 - 05/2025) – performance



Performance of IEX type a (3 filters á 150 L bed volume BV), 96 days

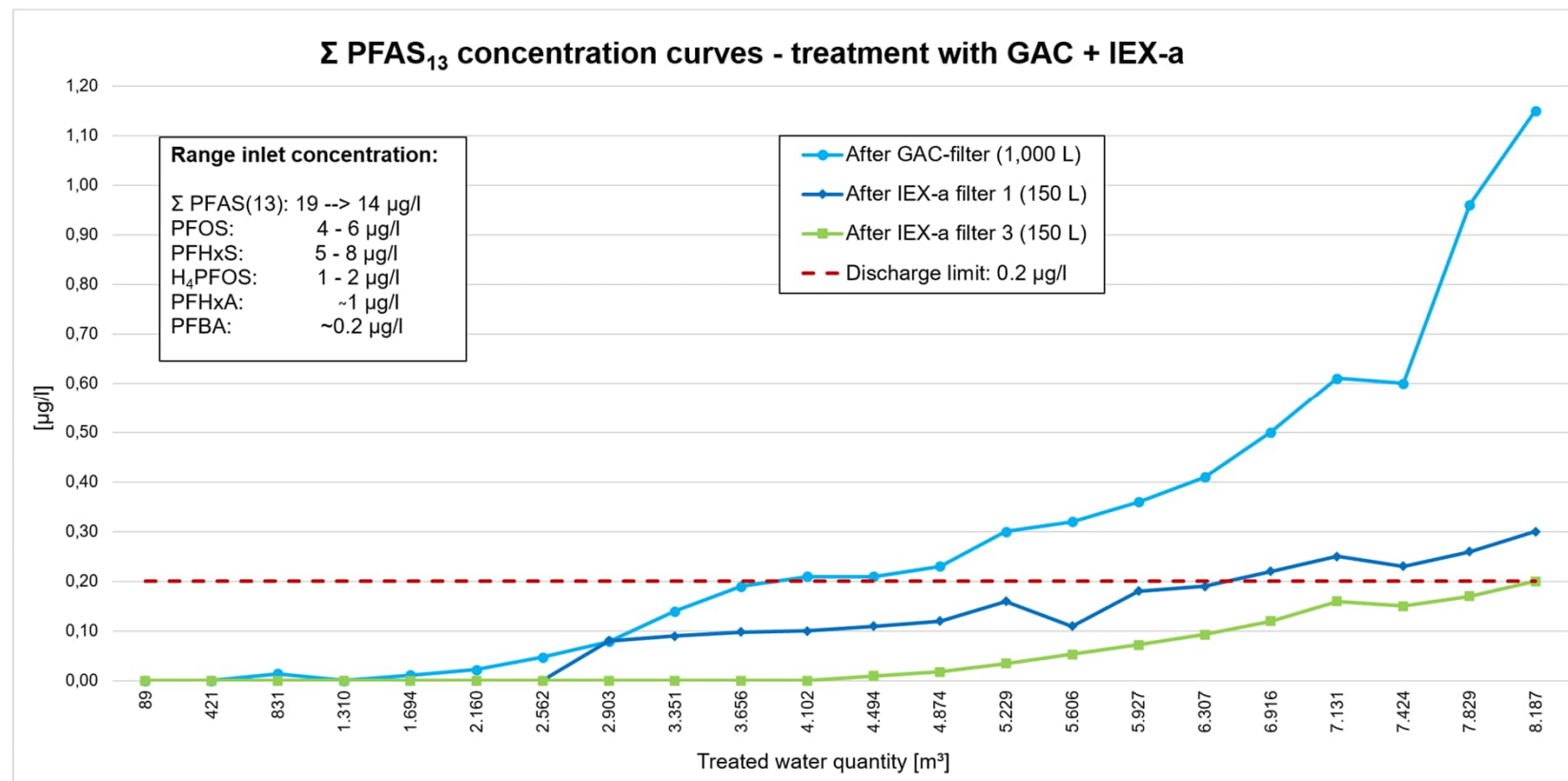
- Freight Σ PFAS₁₃ ~75 g
- Treated water quantity 3,143 m³
- **Exceedance** of discharge limit Σ PFAS₁₃ after IEX-filter no. 3
→ after ~2,600 m³ treated water, respectively ~5,750 BV



Performance of IEX type b (3 filters á 150 L bed volume BV), 104 days

- Freight Σ PFAS₁₃ ~68 g
- Treated water quantity 3,196 m³
- **Exceedance** of discharge limit Σ PFAS₁₃ after IEX-filter no. 3
→ after ~ 3,200 m³ treated water , respectively ~7,100 BV

GAC + IEX-a (05/2025 – 02/2026) – performance



Performance of material combination GAC (1 m³) + IEX type a (3x 0.15 m³) – in total 1.45 m³ bed volume BV, 287 operation days

- Freight Σ PFAS₁₃ ~133 g
- Treated water quantity 8,187 m³
- **Exceedance** of discharge limit Σ PFAS₁₃
→ after ~ 8,180 m³ treated water , respectively ~5,650 BV

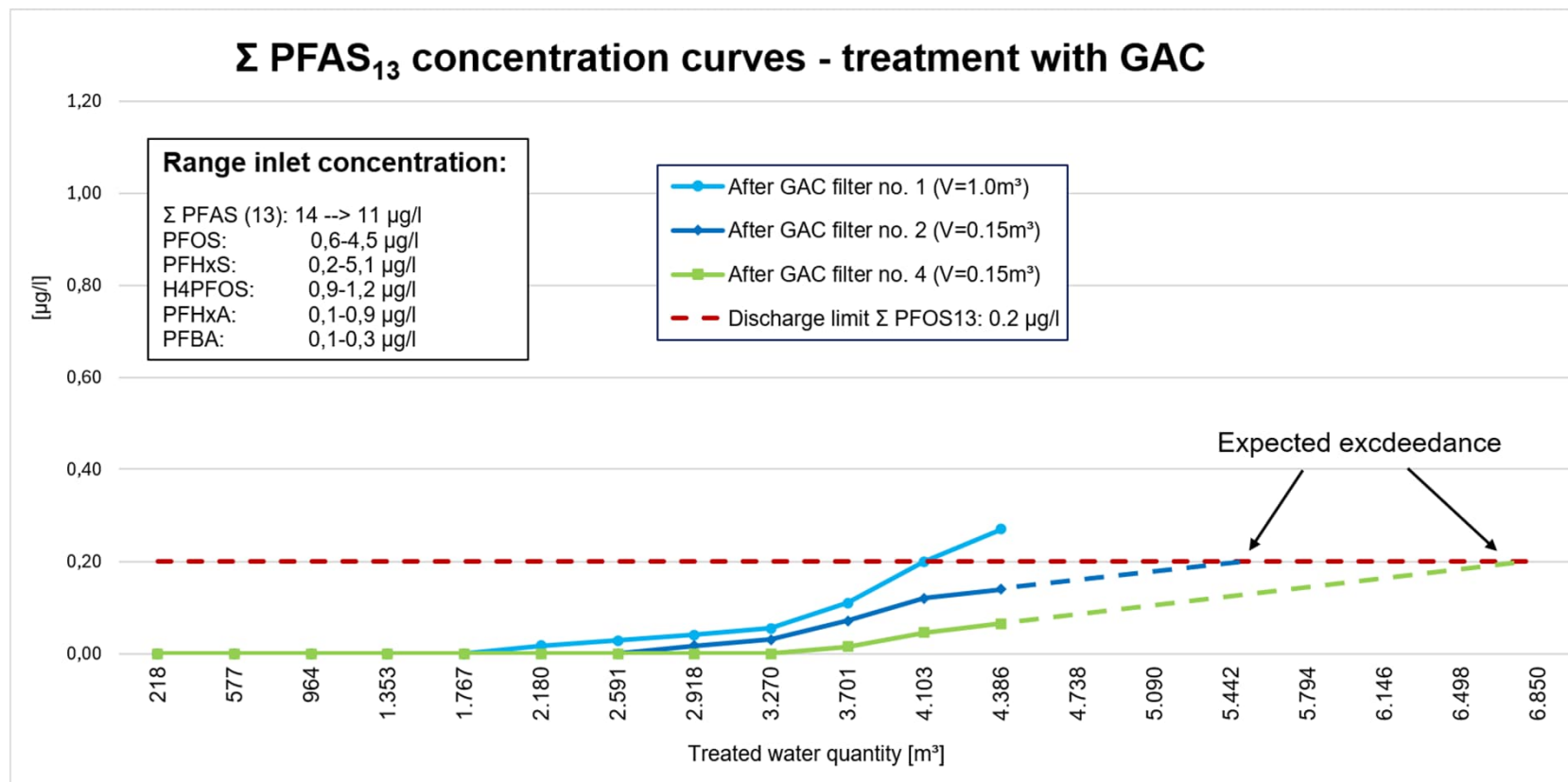
Clay mineral (19/02/2026 – 30/03/2026) – performance

					Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
Acronyms	Parameter	Structure	Type *	Unit	23.02.2026		11.03.2026		23.03.2026	
PFOS	Perfluorooctane sulfonic acid	C ₈ HF ₁₇ O ₃ S	LC	µg/l	38,00	0,00	5,10	0,00	0,25	0,00
PFHxS	Perfluorohexane sulfonic acid	C ₆ HF ₁₃ O ₃ S	SC	µg/l	9,00	0,00	5,00	0,00	3,70	0,00
H ₄ PFOS	1H,1H,2H,2H-Perfluorooctyl sulfonic acid	C ₈ H ₅ F ₁₃ O ₃ S	LC	µg/l	2,20	0,00	0,77	0,00	0,40	0,00
PFHxA	Perfluorohexanoic acid	C ₆ HF ₁₁ O ₂	SC	µg/l	1,50	0,02	0,90	0,12	5,30	0,12
PFPeA	Perfluoropentanoic acid	C ₅ HF ₉ O ₂	SC	µg/l	1,50	0,32	0,59	0,34	0,88	0,33
PFOA	Perfluorooctanoic acid	C ₈ HF ₁₅ O ₂	LC	µg/l	1,10	0,00	0,33	0,00	0,38	0,00
PFHpS	Perfluoroheptane sulfonic acid	C ₇ HF ₁₃ O ₃ S	SC	µg/l	0,41	0,00	0,27	0,00	0,21	0,00
PFBS	Perfluorobutane sulfonic acid	C ₄ HF ₉ O ₃ S	SC	µg/l	0,40	0,00	0,38	0,00	0,00	0,00
PFNA	Perfluorononanoic acid	C ₉ HF ₁₇ O ₂	LC	µg/l	0,16	0,00	0,27	0,00	1,00	0,00
PFBA	Perfluorobutanoic acid	C ₄ HF ₇ O ₂	SC	µg/l	0,46	0,24	0,22	0,18	0,00	0,16
PFDA	Perfluorodecanoic acid	C ₁₀ HF ₁₉ O ₂	LC	µg/l	0,04	0,00	0,00	0,00	0,31	0,00
PFOSA	Perfluorooctane sulfonamide	C ₈ HF ₁₇ O ₃ S	LC	µg/l	0,01	0,00	0,00	0,00	0,25	0,00
PFHpA	Perfluoroheptanoic acid	C ₇ HF ₁₃ O ₂	LC	µg/l	0,57	0,00	0,22	0,00	0,61	0,00
		Σ 13 PFAS		µg/l	56,00	0,58	14,00	0,64	13,00	0,61

Performance of clay mineral (3 filters á 150 L bed volume BV), 39 days

- Freight Σ PFAS₁₃ ~21 g (9 g after 5 days and 170 m³ treated water; lab report dated 2 weeks later)
- Treated water quantity 1,040 m³
- **Exceedance** of discharge limit Σ PFAS₁₃ of 0.2 µg/l after adsorption with clay mineral
→ already noted for 3 SC-PFAS (!) in 1st sampling after 5 days of operation and ~170 m³ treated water, respectively ~380 BV

GAC alone (03/2026 – 07.09.2026) – performance



Performance of material combination GAC alone (1 filter á 1 m³, 3 filters á 0.15 m³ = 1.45 m³ BV), 161 operation days

- Freight Σ PFAS₁₃ ~58 g
- Treated water quantity 4,386 m³
- Exceedance of discharge limit Σ PFAS₁₃ after last GAC filter?
→ No exceedance after ~4,386 m³ treated water , respectively ~3,020 BV
- → Expected exceedance after ~6,700 m³ treated water, resp. ~4,620 BV

Economic assessment - conclusions

Conclusions – comparison of specific treatment cost for IEX, GAC + IEX and GAC

Material	IEX-a	IEX-b	GAC + IEX-a	GAC	Clay mineral
Bed volume	450 L	450 L	1,000 + 450 L	1,450 L	450 L
Water flow	1.35 m ³ /h	1.2 m ³ /h	1.2 m ³ /h	1.4 m ³ /h	1.4 m ³ /h
1st exceedance after	5,750 BV	7,100 BV	5,650 BV	4,620 BV (*)	380 BV
1st exceedance after	2,600 m ³	3,200 m ³	8,180 m ³	6,700 m ³ (*)	170 m ³
Removed PFAS in period	75 g	68 g	133 g	58 g	21 g (SC partially)
Specific PFAS removal capacity	0.029 g / m ³	0.021 g / m ³	0.016 g / m ³	0.009 g / m ³	
Specific PFAS removal capacity	0.013 g / BV	0.010 g / BV	0.024 g / BV	0.013 g / BV	
Specific treatment cost	~6.3 € / m ³	~7.0 € / m ³	~4.6 € / m ³	~4.3 € / m ³	

*: Prognosis

Technical items to evaluate – CAPEX

- Well equipment
- Capacity of the treatment plant – flow-rate to be treated
- Assembly / Disassembly

Economical items to evaluate – OPEX

- Filling of materials (GAC-IEX, etc.)
- Changes of exhausted adsorbent materials
- Utilities (energy, etc.) & Operation and maintenance

General evaluation

- The higher the flow-rate to be treated, usually the lower is the specific price per m³ treated water.
- PFAS water treatment projects usually takes a very long time – so, a longer depreciation of CAPEX can be considered.
- GAC and IAT, in specific cases, could be similar in cost. The combination of both is useful and effective.

Questions?

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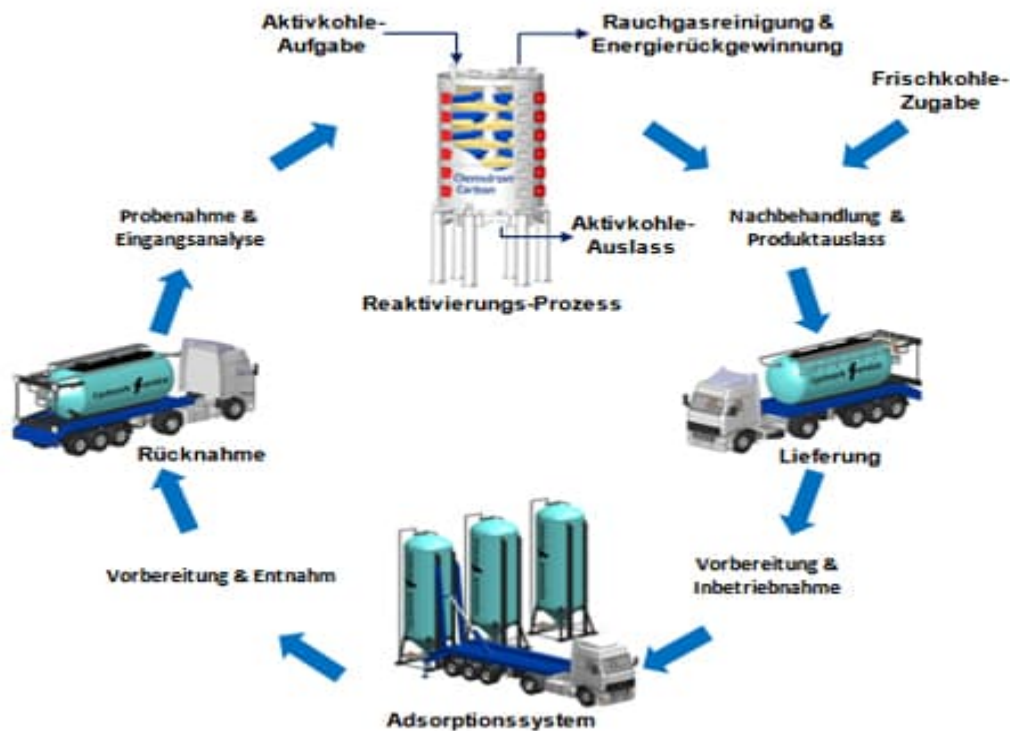
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Reactivation process of PFAS-loaded GAC

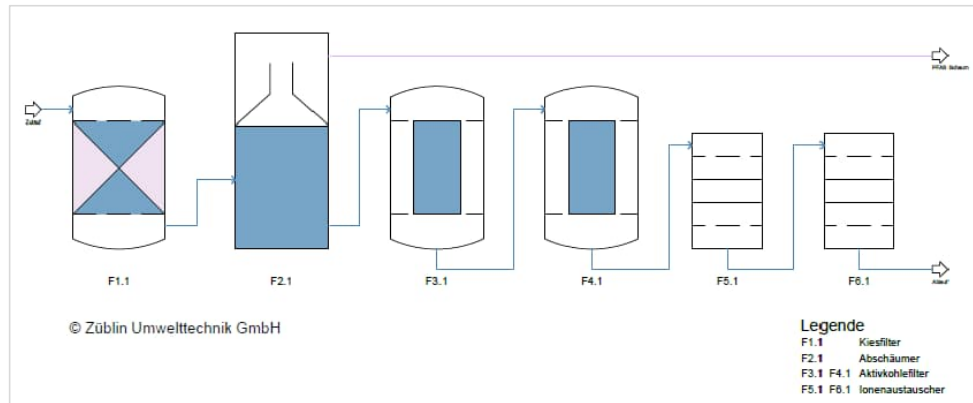
Der Reaktivierungszyklus



- Drying in the oven at approx. 120 °C: Water, low-boiling pollutants evaporate
- Heating in the oven to over 450 °C: Desorption of volatile pollutants
- Further heating to over 600 °C: Pyrolysis of higher boiling org. Pollutants Partial combustion
- Exhaust gas purification by thermal post-combustion at over 1200 °C
- Exhaust gas scrubbing for the removal of acidic exhaust gases such as HCl, HF



Concept for treatment train for PFAS removal from water



Foam fractionation

- High PFAS concentrations/loads
→ Reduction of PFAS load

Activated carbon adsorption

- Low PFAS concentrations/loads
 - Long/short-chain PFAS
 - Fine cleaning

Ion exchange (option)

- Low PFAS concentrations/loads
 - Short/long-chain PFAS
 - fine cleaning

