Ministry of Environment of Denmark
Environmental Protection Agency

Pilot scale demonstration of thermal treatment for the remediation of PFAS contaminated soil Review of key outcomes

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1. Summary

1.1 Summary in English

The Danish Environmental Protection Agency has funded the implementation of pilot tests for demonstration of thermal remediation of PFAS contaminated soil. The demonstration projects have been anchored in the Capital Region of Denmark.

Two thermal methods have been tested. Both pilot projects demonstrated that Thermal Conductive Heating (TCH) effectively remediates PFAS in soil, with all treated samples meeting the Danish soil quality criteria. Soil heated to 350°C or above showed no detectable levels of any PFAS compounds, while samples reaching only 250-300°C retained low residual concentrations. A target temperature of 350°C is recommended for future projects.

The two methods differed in energy source and gas management. Arkil/Haemers used propane-heated pipes with pollutant gases directed through a 1,400°C flame for mineralization. Krüger used electrically heated pipes, retaining vapors in the soil to promote in-situ mineralization and treating remaining gases in a catalytic defluorinator at 600°C for 15 minutes. Both approaches are likely to destroy PFAS, reducing the need for post-treatment, though carbon filter backups were used as a precaution given limited operational experience. Both methods cleaned soil below thresholds, and extensive analysis suggests PFAS destruction occurred, though the fluorine mass balance could not be established because PFAS contributed only about 1% of total soil fluorine.

Targeted PFAS analysis combined with the TOP assay provided a robust picture of contamination and treatment effectiveness. EOF analysis confirmed significant organic fluorine removal. Leaching tests showed 99.9–100% reduction in leachable PFAS and are recommended for evaluating post-treatment groundwater risks, since soil meeting quality criteria can still pose a risk to groundwater.

Non-target screening supported the conclusion that thermal treatment destroyed a broad range of PFAS, but its complexity and slow turnaround make it better suited for research than routine monitoring. Monitoring air emissions using OTM 45 and OTM 50, as well as HRMS, provided insights into the fate of volatile and semi-volatile PFAS during treatment.

The two pilot tests confirmed that thermal remediation methods for PFAS-contaminated soil work as intended, and both approaches are ready for full-scale testing. Full-scale treatment in Denmark will likely involve excavating soil and treating it on-site in piles rather than in-situ.

Large batch sizes of more than 1,000 tons of soil are needed to compete economically with conventional dig-and-haul disposal (~2,000 DKK/ton). Energy efficiency wasn't the focus of these pilots, but larger volumes are expected to bring consumption down to around 350 kWh/ton. Since no full-scale treatment options currently exist in Denmark, it is suggested consolidating contaminated soil from multiple sites at central treatment facilities, which would also simplify the permitting process.

Thermal treatment is most suitable for PFAS hotspots — concentrations exceeding 10 times the soil quality criteria respectively 4,000 µg/kg (Σ22) or 100 µg/kg (Σ4). It may also be justified for lighter contamination in areas with significant groundwater extraction, since leaching tests show even low concentrations can threaten water resources. However, treating all lightly

contaminated soil thermally is unrealistic given that Denmark has identified up to 15,000 potentially affected sites.

The technology works for both sandy and clayey soils, and while its competitiveness against soil washing in sand hasn't been studied, it is the stronger option for clay where soil washing is unsuitable. Thermal treatment is also a more responsible alternative to landfilling, as it is likely to destroy PFAS permanently rather than relocating it. The approach may also suit PFAS-contaminated sludge, filter cake, or mixed-contaminant soils, but it has not been investigated in this project.

1.2 Summary in Danish

Miljøstyrelsen har finansieret udførelsen af pilotforsøg til demonstration af termisk oprensning af PFAS-forurenet jord. Demonstrationsprojekterne har været forankret i Region Hovedstaden.

To termiske metoder er blevet testet. Begge pilotprojekter viste, at termisk opvarmning effektivt oprenser PFAS i jord, idet alle jordprøver udtaget og analyseret efter oprensningen opfyldte de danske jordkvalitetskriterier. Jord opvarmet til 350°C eller derover viste ingen påviselige niveauer af PFAS-forbindelser, mens jordprøver, der kun nåede 250-300°C, indeholdt PFAS i lave koncentrationer under jordkvalitetskriterierne. En måltemperatur på 350°C anbefales til fremtidige projekter.

De to metoder adskilte sig i energikilde og håndtering af de afdampede gasser fra jorden. Arkil/Haemers opvarmede rørene i jorden vha. gas (propan). Forurenende gasser fra jorden blev ledt gennem en 1.400°C flamme til mineralisering. Krüger brugte elektrisk opvarmning. Opvarmningen skete langsomt og tilbageholdt PFAS i jorden for at fremme in-situ mineralisering. Gasser blev behandlet i en katalytisk defluorinator ved 600°C i 15 minutter. Begge tilgange vil sandsynligvis destruere PFAS, hvilket reducerer behovet for efterbehandling, selvom kulfiltre som backup blev brugt som en sikkerhedsforanstaltning i betragtning af begrænset operationel erfaring.

Ved begge metoder blev jorden renset til under jordkvalitetskriterierne, og omfattende analyser tyder på, at der forekom PFAS-destruktion, selvom fluormassebalancen ikke kunne opstilles, fordi PFAS kun bidrog med omkring 1% af jordens samlede fluor indhold.

Målrettet PFAS-analyser kombineret med TOP-analyser gav et robust billede af forurening og behandlingseffektivitet. EOF-analyse bekræftede betydelig fjernelse af organisk fluor. Udvaskningstest viste en reduktion på 99,9-100% i forhold til mobile PFAS-stoffer og anbefales til evaluering af grundvandsrisici efter behandling, da jord, der opfylder jordkvalitetskriterierne, stadig kan udgøre en grundvandsrisiko.

Non-target screening understøttede konklusionen om, at termisk behandling destruerede en bred vifte af PFAS-stofferne, men analysemetodens kompleksitet og langsomme ekspeditionstid gør den bedre egnet til forskning end rutinemæssig monitering. Overvågning af luftemissioner ved hjælp af OTM 45 og OTM 50, samt HRMS, gav indsigt i skæbnen for de flygtige og semi-flygtige PFAS-stoffer under oprensningen.

De to pilotforsøg bekræftede, at termiske oprensningsmetoder for PFAS-forurenet jord fungerer og begge tilgange er klar til fuldskalaforsøg. Fuldskalabehandling i Danmark vil sandsynligvis involvere udgravning af jord og behandling af den på stedet i miler i stedet for in-situ.

Store jordmængder på over 1.000 tons er nødvendige for at kunne konkurrere økonomisk med konventionel bortskaffelse ved opgravning og deponering (~2.000 kr./ton). Energieffektivitet var ikke i fokus for disse pilotprojekter, men større jordmængder forventes at bringe energiforbruget ned på omkring 350 kWh/ton. Da der i øjeblikket ikke findes fuldskala

behandlingsmuligheder i Danmark, foreslås det at samle forurenet jord fra flere steder på et centralt behandlingsanlæg, hvilket også ville forenkle processen i forhold til myndighedstilladelser.

Termisk behandling er mest egnet til PFAS-hotspots — koncentrationer på over 10 gange jordkvalitetskriterierne dvs. 4.000 µg/kg (Σ22) eller 100 µg/kg (Σ4). Det kan også være berettiget til lettere forurenet jord i områder med betydelig grundvandsindvinding, da udvaskningstest viser, at selv lave jordkoncentrationer kan være en risiko for grundvandsressourcen og vandindvinding. Det er dog urealistisk at behandle al lettere forurenet jord termisk, da Danmark har identificeret op til 15.000 potentielt forurenede lokaliteter.

Teknologien fungerer til både sand- og lerjord, og selvom dens konkurrenceevne i forhold til jordvask for sandjord ikke er blevet undersøgt, er det en bedre løsning til lerjord, hvor jordvask er uegnet. Termisk behandling er også et mere ansvarligt alternativ til deponering, da det vil destruere PFAS-stofferne permanent. Tilgangen kan også være egnet til PFAS-forurenet slam, filterkage eller jord forurenet med forskellige forureningskomponenter, men det er ikke blevet undersøgt i dette projekt.

2. Introduction

The Danish Environmental Protection Agency has funded the implementation of two pilot tests for demonstration of remediation of PFAS contaminated soil. The demonstration projects have been anchored in the Capital Region of Denmark. WSP has provided assistance and advice in relation to the task description, supervision during the execution and preparation of this evaluation report.

The projects have been followed by a project group consisting of representatives from all 5 Danish regions and the Regional Knowledge Centre for Environment and Resources. The project group consists of the following people:

Henrik Giversen Nordtorp, North Jutland Region
Thomas Ljungberg, Central Denmark Region
Klaus Bundgaard Mortensen, Region Southern Denmark
Martin Engelmann Pedersen, Region Zealand
Bente Hyldegaard, Region Zealand
Mads Georg Møller, Capital Region
Line Mørkebjerg Fischer, Capital Region
Julie Kofoed, Regional Knowledge Centre for Environment and Resources

The methods that have been tested are both thermal methods. The Danish company Arkil, in collaboration with the Belgian company Haemers Technologies, has tested thermal remediation, where gas is used to heat the soil and for destruction of the PFAS.

The Danish company Krüger, which is part of a French multinational company Veolia Group, has tested thermal remediation, where electricity is used to heat the soil. The methods are briefly described in Chapter 3. The reports from Arkil / Haemers and Krüger are attached in appendix 1 and 2, respectively.

The two pilot tests were carried out at the former Korsør Fire Academy, from which PFAS-contaminated soil was excavated and delivered.

The former Korsør Fire Academy is a national PFAS test Center. Site investigation reports and other information about the test Center can be accessed via the website:

https://www.miljoeogressourcer.dk/testsite/11

2.1 Background

Disposal of PFAS-contaminated soil is difficult, both in terms of sustainability, lack of facilities and high costs. Only heavily contaminated soil can be sent for chemical destruction at special thermal treatment facilities. In addition, this requires the soil to be excavated and transported, and the capacity of such facilities is limited. There is a need for alternative treatment methods for the remediation of PFAS-contaminated soil that are technically- and cost-effective, and sustainable.

Model calculations have shown that transport of long-chain sulfonic acids, such as PFOS, through the unsaturated zone in the soil is slow – so slow that the majority of PFOS spilled in the early 1960s probably have only reached a few meters into the ground (Capital Region 2023).

A study from Canada (mentioned in Capital Region 2023), where samples were taken of both near-surface groundwater and pore water in the unsaturated zone just above the groundwater table, has also shown that the PFAS concentration is 8-14 times higher in the pore water than in the groundwater. These experiments and studies indicate that the PFAS content detected in the groundwater at some sites today may only be the "tip of the iceberg", because a large part of the long-chain PFAS have not yet reached the groundwater.

Studies on PFAS contaminated soils have shown that even relatively low PFAS contents in soil can lead to exceedances of the quality criteria in the groundwater of 2 ng/l (Σ4; PFOS, PFOA, PFNA, PFHxS). Quality criteria for PFAS in soil are relatively high at 10 µg/kg DM for Σ4 PFAS, and therefore most exceedances of current standards are found in the groundwater (Capital Region 2023). Despite this, remediation of PFAS contaminated soil can be an advantageous to minimize leaching to the groundwater, which in Denmark is used for drinking water.

There are projects underway in Denmark and elsewhere regarding soil washing of PFAS contaminated soil. The preliminary results indicate that soil washing is best suited for sandy sediments (Capital Region 2023). A large part of the PFAS impacted soil in Denmark consists of moraine clay, which generally is challenging to treat. When soil washing, there is also a relatively large fraction that must be post-treated or deposited.

In this project, the project group has required that the remediation method must be applicable to both sandy and clayey soils. The project group has also required that the PFAS must be destroyed, i.e. immobilization techniques, where the PFAS in the soil is stabilized or encapsulated, have not been considered in this program.

At the time of initiation of this program (winter 2023) it was assessed that there were no technologies available that are at a level of development where an actual in situ project could be carried out with full confidence in the positive results. A dialogue with relevant vendors showed that several actors have technologies ready for pilot testing, e.g. in a container /small scale.

Following an open tender, two thermal treatment technologies were selected for the destruction of PFAS contamination in soil. Thermal remediation can be used in both moraine clays and more sandy soil types. Thermal remediation of PFAS contaminated soil has previously been tested on a laboratory scale. In this project, thermal remediation of PFAS contaminated soil has been tested on a pilot scale.

2.2 Aim

The aim of the project is to test the remediation of PFAS contaminated soil at the former Korsør Fire Academy, which is a national PFAS test Center for the testing of methods for investigation and treatment of PFAS contaminated soil and groundwater.

Based on the two performed pilot tests, the technologies will be assessed in terms of treatment efficiency. This is the primary purpose of the demonstration projects. Secondly, some considerations will be made in relation to sustainability, usability and the possibility of scaling up.

The tested treatment technologies must be able to effectively clean the PFAS contaminated soil to below the Danish Environmental Protection Agency's quality criteria for soil, which are 10 µg/kg for PFAS Σ4 (sum of PFOS, PFOA, PFHxS and PFNA) and 400 µg/kg for PFAS Σ22.

It is important to the project that:

1. thorough documentation of the tested technologies is provided
2. the removal of PFAS is documented and generation of byproducts is accounted for
3. the technology provider strives to close the fluorine mass balance (*)

Hence, the project group has defined analytical packages to be applied for the various waste streams to ensure a high level of documentation. A secondary aim of the project is to obtain hands-on experiences and insights from novel analytical procedures.

*: The initial project scope regarding the closing of the fluorine mass balance was revoked in the tender phase, Q&A question 318902: Considering the recent soil data analysis from the site where fluoride concentrations in the soil are approx. 5-10 mg/kg we realize that it is not feasible to establish a fluorine mass balance. However, the tenderer is encouraged to describe an analytical program that can show documentation for PFAS destruction, that could include TOP-assay analysis or other methods.

3. Description of the two thermal pilot tests

This chapter describes the technologies and methods tested to remediate PFAS-contaminated soil at the former Korsør Fire Academy. From this point forward, these technologies will be identified by the names of their respective suppliers: Arkil / Haemers and Krüger.

Both Arkil / Haemers and Krüger use Thermal Conductive Heating (TCH). TCH is a method of heat transfer where energy moves through a material or between materials in direct contact without the material itself moving. At its core, thermal conduction is the process of heat flowing from a hotter region to a colder region due to a temperature gradient.

For this pilot targeting PFAS-compounds, both methods involve heating the soil to a target temperature of 350 °C using heater pipes that distribute the heat into the soil volume. Differences between the two methods is the energy source and how PFAS is destroyed. Both methods are described in the following sections. Arkil / Haemers' report is attached in Appendix 1. Krügers report is attached in Appendix 2.

3.1 Arkil / Haemers

Arkil / Haemers used propane powered burners to create hot air for heating the soil. The pilot unit was housed in a 20-foot insulated container - capable of containing 15 m^3 of soil.

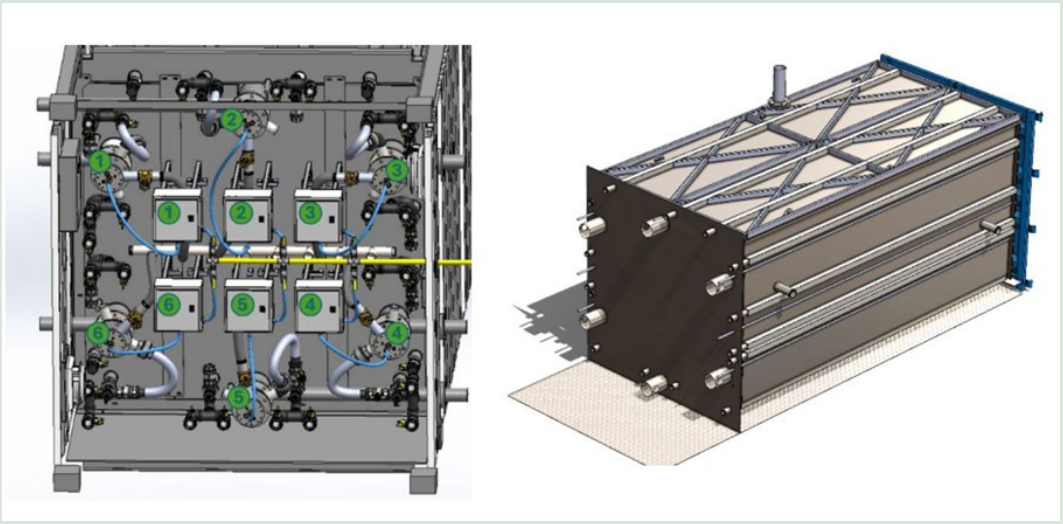


FIGURE 1. Front of the container with heater pipes and Smart Burner control boxes (left) and side view with heater pipes and extraction pipes (right).

The heating of the soil occurs relatively quickly. In about 2 weeks, the soil is heated to the target temperature of minimum 350 °C, and the temperature is then maintained for an additional 14 days. The total treatment time is approximately 1 month.

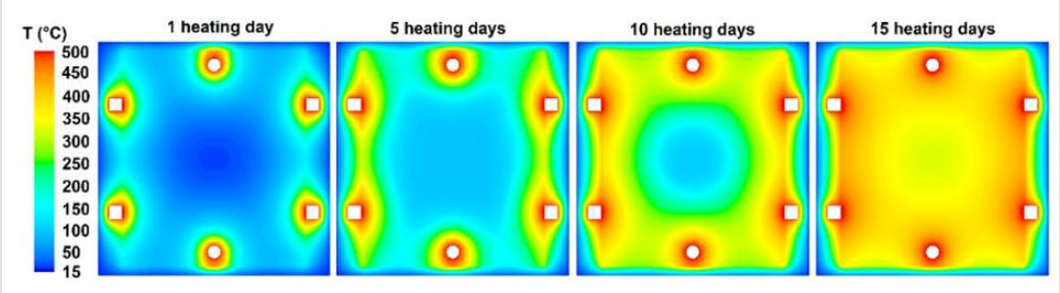


FIGURE 2. Expected development in the temperature distribution in the soil volume.

In the pilot project, Arkil / Haemers measured soil temperature using 4 thermocouples located along the center point (cold point) of the pilot unit for continuous measurements of temperature development in the soil. Arkil / Haemers also had several temperature sensors measuring burner temperature.

Temperatures achieved in the test are shown in section 3.3.

The pilot test setup is shown in the figure below:

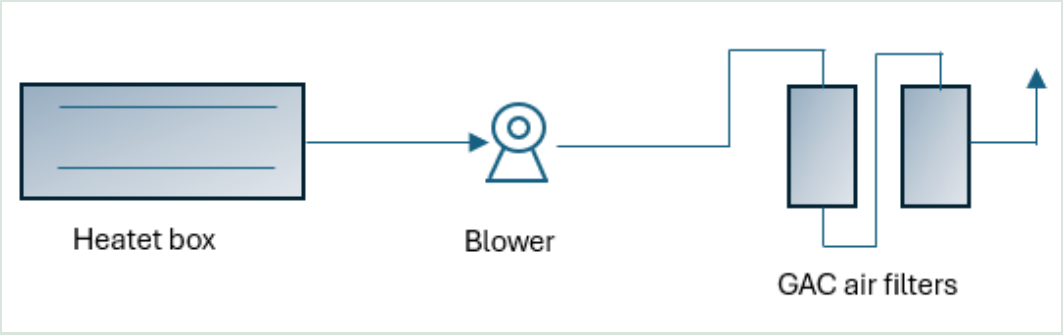


FIGURE 3. Arkil / Haemers pilot test setup. Reburn in the heatet box (see figure 4).

The evaporated gases are extracted using slotted pipes in the soil volume and the gas is routed through the flame for high temperature combustion (1,400 °C) in the same burner system which provides energy for the heating of the soil. Reburn in the flame (within the heated container), as well as sampling points, are shown in figure 4.

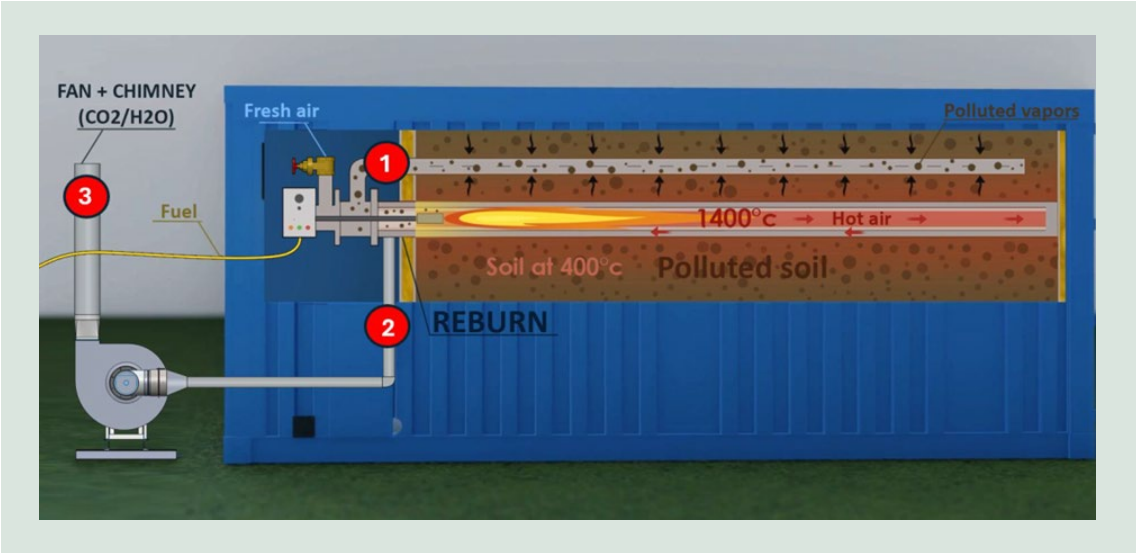


FIGURE 4. Cross section of heated box with heater pipe and extraction pipe. Numbers are sampling ports for gas sampling.

Thermal destruction of PFAS depends on both temperature and residence time. A common benchmark is 2 seconds at 1,400 °C, but this represents an average requirement rather than a fixed condition. In the Arkil/Haemers system, vapors are exposed to varying temperatures: very high temperatures (up to ~1,600 °C) for a short time when passing through the flame, followed by longer exposure at lower temperatures. This combination of brief high-temperature peaks and longer moderate-temperature residence provides the equivalent conditions needed for efficient PFAS destruction.

The exhaust gas was treated by passing it through filters containing EcoSorb CS granular activated carbon (GAC) to capture any unintended degradation products.

3.2 Krüger

In Krügers set-up, electricity was used for the heating process. Krügers remediation was also carried out in a 20-foot insulated container / heated box. The PFAS-contaminated soil in the container was heated to a temperature of approximately 350-450 °C.

The process when heated using electricity is divided into a drying phase, a temperature ramp-up phase and a holding phase.

Krüger heats up slowly and thus breaks down some of the PFAS substances in the soil and therefore reduces what comes out of the soil. The slow heating process comprising of separate drying, temperature ramp-up and constant temperature holding phases lasts a total of 3 months.

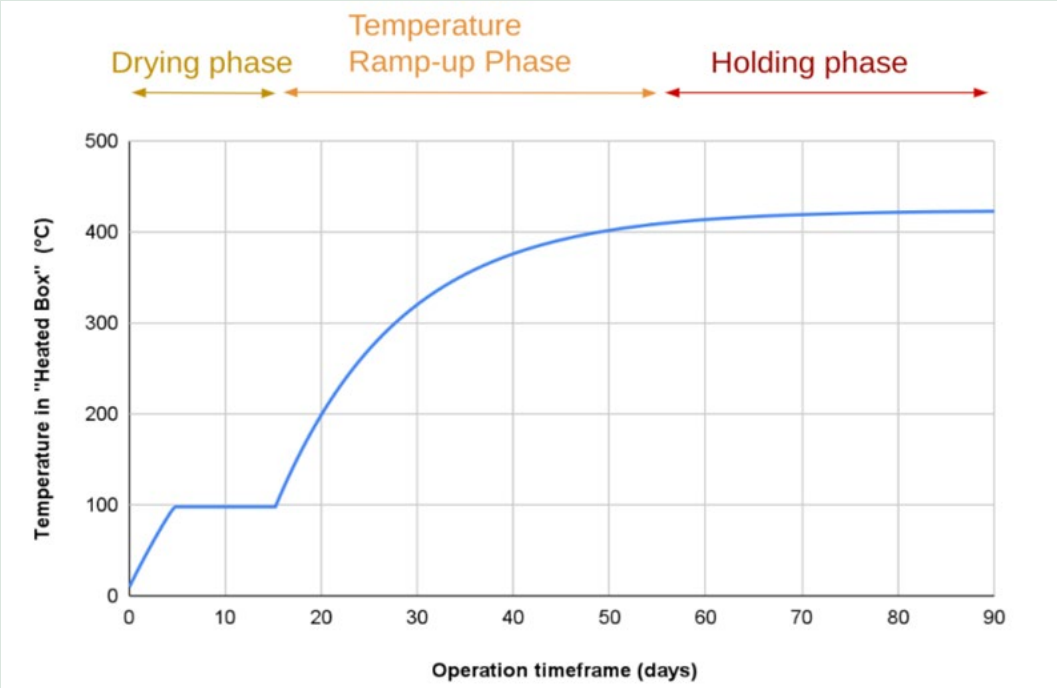


FIGURE 5. Expected average soil temperature development.

In the pilot project, Krüger had installed 29 sensors / temperature measurement points in the container where continuous measurements of temperature development were carried out. 18 sensors were placed in the areas between the heating pipes, and 11 sensors were placed along the heating pipes. In addition, Krüger had 21 measuring points on the outside of the box under the insulation. Temperatures achieved in the test are shown in chapter 3.3.

As shown in figure 6 vapor was heat treated in the defluorinater (straight from the heated box), cooled and scrubbed (mild alkaline) and finally GAC filtered.

The vapor extracted from the soil was directed to a catalytic defluorinator and held at 600 °C for approx. 15 minutes to defluorinate volatilized PFAS. Temperature distribution for the defluorinator is measured over time and over height of the container (multiple measuring points). It is a 2 m high Ø400 mm container (250 L). With a flow of 1 Nm3/h, a nominal empty bed residence time of 15 min is obtained.

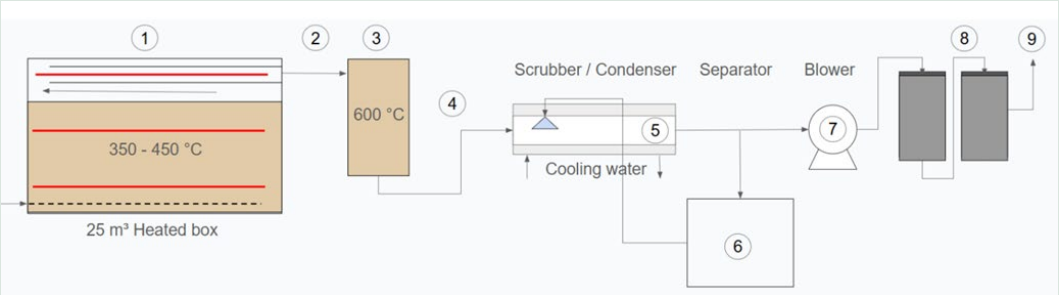


FIGURE 6. Pilot test setup. 1) Heated Box. 2) Sampling point at the Heated Box outlet. 3) Catalytic DeFluorinator.4) Sampling point at the deflourinator outlet. 5) Air quench, scrubbing and cooling to ambient temperature. 6) Condensate tank for neutralisation and quench loop. 7) Blower 8) GAC air filters. 9) Sampling point in stack.

The exhaust gas was treated in filters with Granular Activated Carbon (GAC) to collect any unintended degradation products. Condensate was collected in 1 m^3 tanks in the drying phase.

3.3 Operating data

The two pilot tests were carried out at the former Korsør Fire Academy, from which PFAS-contaminated soil was excavated and delivered. A total of 62 tons of soil was excavated at depths of 0-2.5 m. The soil was homogenized by placing soil containers next to each other and filling the containers with soil alternately. During the excavation, it was also attempted to have soil from the terrain down to a depth of 2.5 m distributed evenly in the containers.

The soil was delivered to Arkil / Haemers and Krüger (31 tons each), who filled the soil into their own pilot unit (heated box). Krüger could have all the soil in their heated box. Arkil / Haemers chose to run 2 batches. Batch 1 contained 15 m3 of soil corresponding to approximately 27 tons of soil. Batch 2 also contained approximately 27 tons of soil, but it was approximately 4 tons of untreated soil and 23 tons of soil from batch 1, which had been treated once.

Analysis data in relation to soil, air and water (condensate) are described in Chapter 4. Condensate was not expected in Arkil/Haemers pilot test, but a small amount of condensate (a few liters) was generated. When operation became stable, no more condensate was formed.

In Krüger's pilot test condensate was collected in 1 m3 tanks in the drying phase. A total of 4,400 liters were collected, of which 600 liters came from the oxidation and pyrolysis of organic matter. In addition, 400 liters of water were used to clean the tanks. This resulted in 4,800 liters of water being delivered for purification in the on-site plant at the Former Korsør Fire Academy operated by Ultra Aqua.

Important operating data is the temperature measurements in the soil. In the pilot project, Arkil / Haemers had installed 4 temperature measurement points in the container for continuous measurements of temperature development in the soil. Temperatures achieved in the test are shown in figure 7.

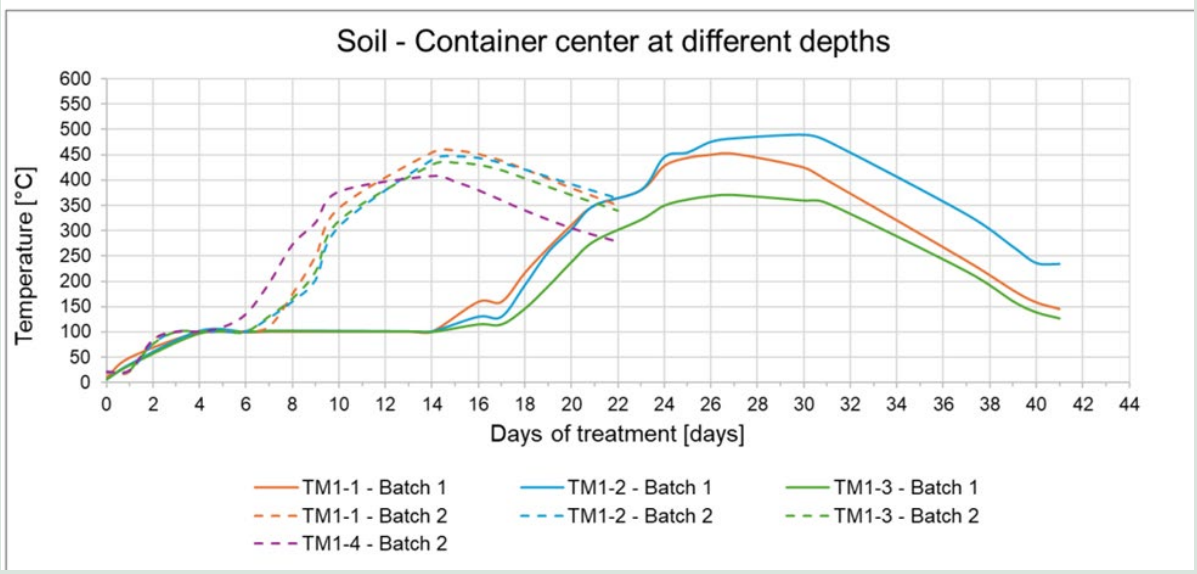


FIGURE 7. Temperature obtained in the pilot test by Arkil/Haemers.

Krüger had installed 29 temperature measurement points in the container for continuous measurements of temperature development in the soil (18) and heaters (11). Temperatures achieved in the test are shown in figure 8. Additionally, the box surface temperature was also measured.

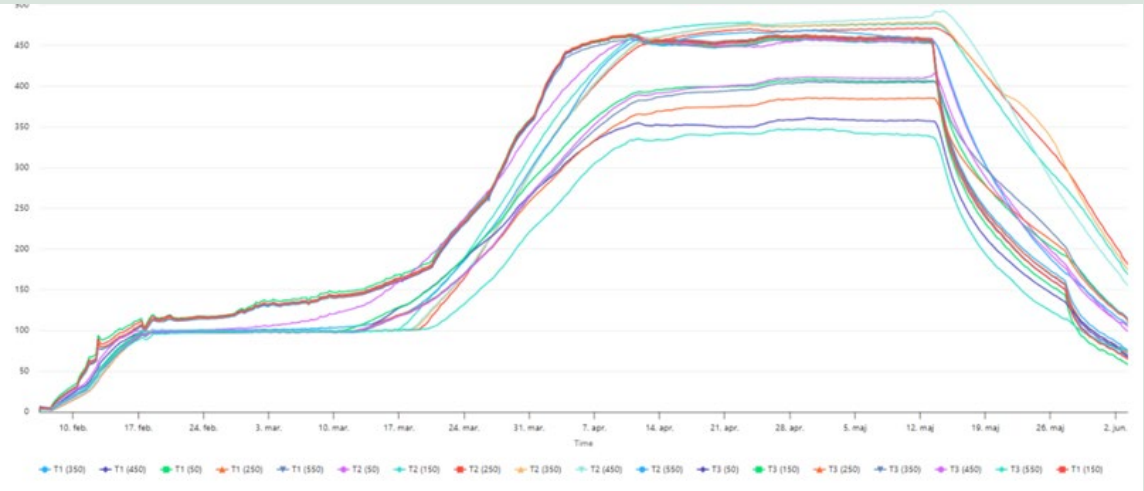


FIGURE 8. Temperature obtained in the pilot test by Krüger.

The temperatures obtained are generally quite similar. The difference is mainly the number of temperature monitoring points. In the Arkil / Haemers set up, 4 monitoring points were placed in the center of the box at the expected coldest point. Therefor there is little information on the exact temperature at the container's boundaries.

The observed temperature profiles in the two pilot tests are generally similar, showing an initial heating phase in which temperatures rise to a plateau around 100 °C as water evaporates. Once the water has been removed, the temperature increases further to the target of minimum

350 °C, where it is maintained for a period. The total heating duration was approximately 1 month for the Arkil/Haemers pilot test and 3 months for the Krüger test.

In Krügers pilot test temperature distribution throughout the soil during the holding period is shown in figure 9.

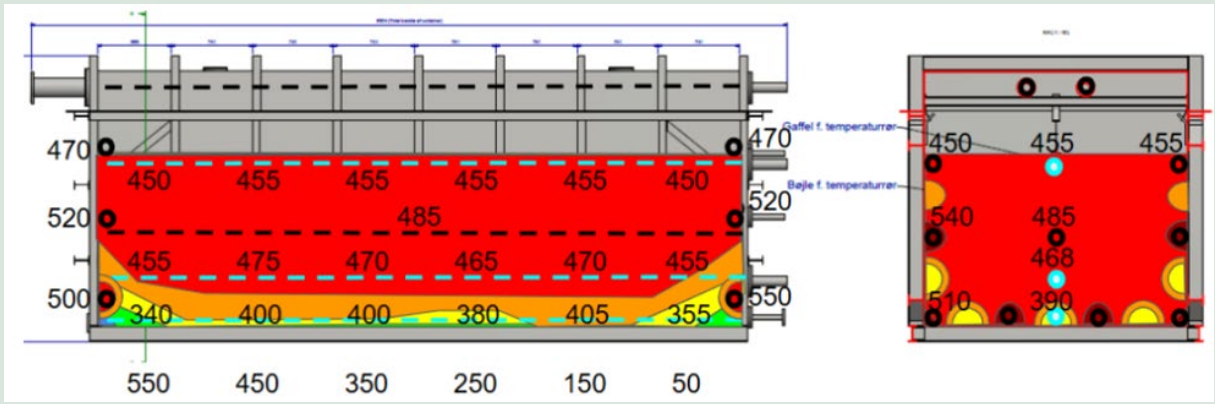


FIGURE 9. Temperature distribution throughout the soil during the holding period

The soil temperature exceeded 350 degrees at all measurement points except one in the corner of the container (green areas), where it is estimated that the temperature is about 250-300 degrees.

4. Results and discussion

This chapter offers a summary of findings from both tests. While each test met documentation requirements, differences in their setups mean that data such as flow and temperature are not always directly comparable across all measurements. The aim here is not to compare the methods but to highlight key results. Whenever detailed information is available from one test, it is included in this chapter, even if equivalent data is not accessible from the other method.

4.1 Monitoring program for soil and waste streams

Both projects received excavated soil that had been characterized by WSP. Baseline results for the soil are summarized in chapter 4.2. and shown in detail in Appendix 1 (Arkil/Haemers report) and Appendix 2 (Krügers report).

A key evaluation parameter for the pilot tests was to acquire enough evidence to clarify the fate of the PFAS treated. Therefore, an extensive analytical program pre- and post-treatment was required.

Minimum requirements for post-treatment analysis according to the tender task description were:

- At least 1 composite sample per ton of treated soil to be analysed for PFAS 22 by an accredited laboratory. Detection limit <1 µg/kg for each individual PFAS in PFAS 22, but <0,5 µg/kg for PFOS, PFNA, PFOA and PFHxS. Composite samples should consist of five subsamples.
- At least 3 TOP (Total oxidizable precursor) assay analysis of composite soil samples post treatment. We suggest TOP assay for at least 35 PFAS.
- Analysis of PFAS 22 for any waste streams (wastewater, sludge, soil, vapor) generated during the treatment.
- At least one TOP Assay analysis of any relevant waste stream.

Furthermore, the two projects supplemented their program with non-target analyses and Extractable Organo-Fluorine (EOF) analyses. Krüger also applied a real time High-Resolution Mass Spectrometry (HRMS) for monitoring fluorinated compounds, with limited success (see details in 4.7.3).

As heat was exclusively used as the treatment method, without addition of any other chemical reagents, it was unnecessary to evaluate residual reagents, degradation products of such, or related toxicity.

For Krügers project, the primary waste streams comprised vapors and condensate, including condensate sludge. Additionally, Krüger incorporated a granular activated carbon filter and a catalyst within the defluorinator, which were both included in the monitoring program.

For Arkil / Haemers project, the primary waste stream was vapor. A granular activated carbon filter was installed as back-up before the chimney. A few liters of condensate were collected from purge valves due to start-up / operational issues during batch 1. Arkil / Haemers

performed tests in two batches and the monitoring and analytical program was adjusted, to document the treatment efficiency and remaining PFAS in waste streams, for both batches.

An Overview of the number of samples analysed during different treatment steps and parameters incl. the detection limits of the parameters are shown in Table 1. Both vendors complied with the minimum requirements of the analytical program.

TABLE 1. Overview of the monitoring program, number of analyses.

			KRÜGER		ARKIL/HAEMERS		
	Parameter	**Detection Limit**	**Baseline/ Before treatment**	**During /After treatment**	**Baseline/ Before treatment**	**after first batch**	**after second batch**
Soil	**PFAS 22**	0.03-1 µg/kg DM	36	36	36	19	18
	PFAS 30/35 [A]	0.5-1 µg/kg DM	3	3	3	3	
	PFAS 35 TOP assay	0.01-1 µg/kg DM	3	3	3	3	3
	NTS PFAS	N/A - semiqualitative analysis	3	3	4	4	
	EOF	50 µg/kg DM	3	3	3	2	2
	Dissolvable fluoride	1 mg/kg DM	3	3	3	0	0
	Desorption tests PFAS and ultrashort PFAS	Detection limit not specified	1	1	1	1	0
Vapor /Exhaust gas	**HRMS**	N/A - qualitative analysis		Continuous		0	0
	OTM45	0.1 ng/ m^3		3		3	0
	OTM50	3.2 ppb v/v 5-60 µg/m^3		3		3	0
Spent GAC	**PFAS 22**	1 µg/kg DM		1		0	1[B]
	PFAS 30/35	Detection limit not specified		0		0	1[B]
	PFAS 35 TOP assay	Detection limit not specified		0		0	1[B]
	NTS	Detection limit not specified		0		1	0
Condensate	**PFAS 22**	0.2-1 ng/l		6		1[C]	0
	PFAS 30/35	0.3-2 ng/l		3		1[C]	0
	PFAS 35 TOP assay	0.3-2 ng/l		3		1[C]	0
	NTS PFAS	N/A - semiqualitative analysis		3		0	0
	AOF	1 µg/l		3		1[C]	1[C]
	Dissolved fluoride	50 µg/l		3		0	0

			KRÜGER		ARKIL/HAEMERS		
	Parameter	Detection Limit	Baseline/ Before treatment	During /After treatment	Baseline/ Before treatment	after first batch	after second batch
Condensate sludge	PFAS 22	0.5-1 µg/kg DM		1		No sludge generated by this method	
Defluorinator Catalyst	PFAS 30/35	0.5-1 µg/kg DM		1		No catalyst involved in this method	
	PFAS 35 TOP assay	0.5-1 µg/kg DM		1			
	Dissolvable fluoride	1 mg/kg DM		1			
	[A] PFAS 30/35. Arkil Haemers samples underwent TOP assay testing for 30 PFAS compounds. The same samples were also analyzed for PFAS using an analytical method covering 35 PFAS compounds, which includes the 30 measured after the TOP assay. Krüger's samples were analyzed for 35 PFAS pre and post TOP. [B] Granular Activated Carbon served as back-up only and was reused between batch 1 and batch 2. Samples retrieved after batch 2 were thus exposed to vapors from both batches. [C] Very little condensate was generated in the Arkil/Haemers test, therefore fewer analysis was performed.						

4.2 PFAS concentrations in soil before treatment

Both vendors received excavated soil that had been characterized by WSP.

A summary of the analytical results for PFAS in the soil is presented in Table 2. Average values and standard deviations were calculated for the 18 subsamples. It is surprising that the composite samples for container 3, sent to PFAS30/35 and TOP assay, show a lot lower concentrations of PFAS than the average of the 18 subsamples. Standard deviation for container 3 is also much higher. There is therefore some indication that container three was not as well mixed as the other three containers. Sampling was performed by WSP.

TABLE 2. Baseline average concentrations of PFAS (µg/kg) in soil before treatment.

	Container 1 (Arkil Haemers)	Container 2 (Krüger)	Container 3 (Krüger)	Container 4 (Arkil Haemers)
PFAS 4	183 ± 33	177 ± 27	160 ± 73	73 ± 20
PFAS 22	208 ± 34	204 ± 25	176 ± 74	85 ± 20
PFAS 35*	201	207	76	107
PFAS 30*	200	206	76	107
PFAS 30 TOP excl. LoQ	248	208	64	133
EOF	207**	203***	203***	unknown
*PFAS 30/35. Arkil Haemers samples underwent TOP assay testing for 30 PFAS compounds. The same samples were also analyzed for PFAS using an analytical method covering 35 PFAS compounds, which includes the 30 measured after the TOP assay. Krüger's samples were analyzed for 35 PFAS pre and post TOP **average of two samples ***Average of three samples sent to analysis by Krüger				

In general, the contamination degree of all containers was within the same range, although container 4 delivered to Arkil- Haemers deviated. The standard deviation of the subsamples for each container was be-tween 12 and 42 % despite the homogenization of the soil.

As shown in Table 2, PFAS 4 is predominant in the untreated soil. The composition is mainly dominated by PFOS. The larger analytical package (PFAS 35) showed a moderate increase of the total PFAS concentration. TOP assay results showed that most of the precursors are already transformed as the total PFAS concentrations increased by up to 24 %. However significant additional PFBA (20-100 times higher molar concentration) was generated, possibly from 6:2 FTS /5/ or other precursors. An illustration of the development in concentrations before and after TOP can be seen in Figure 10.

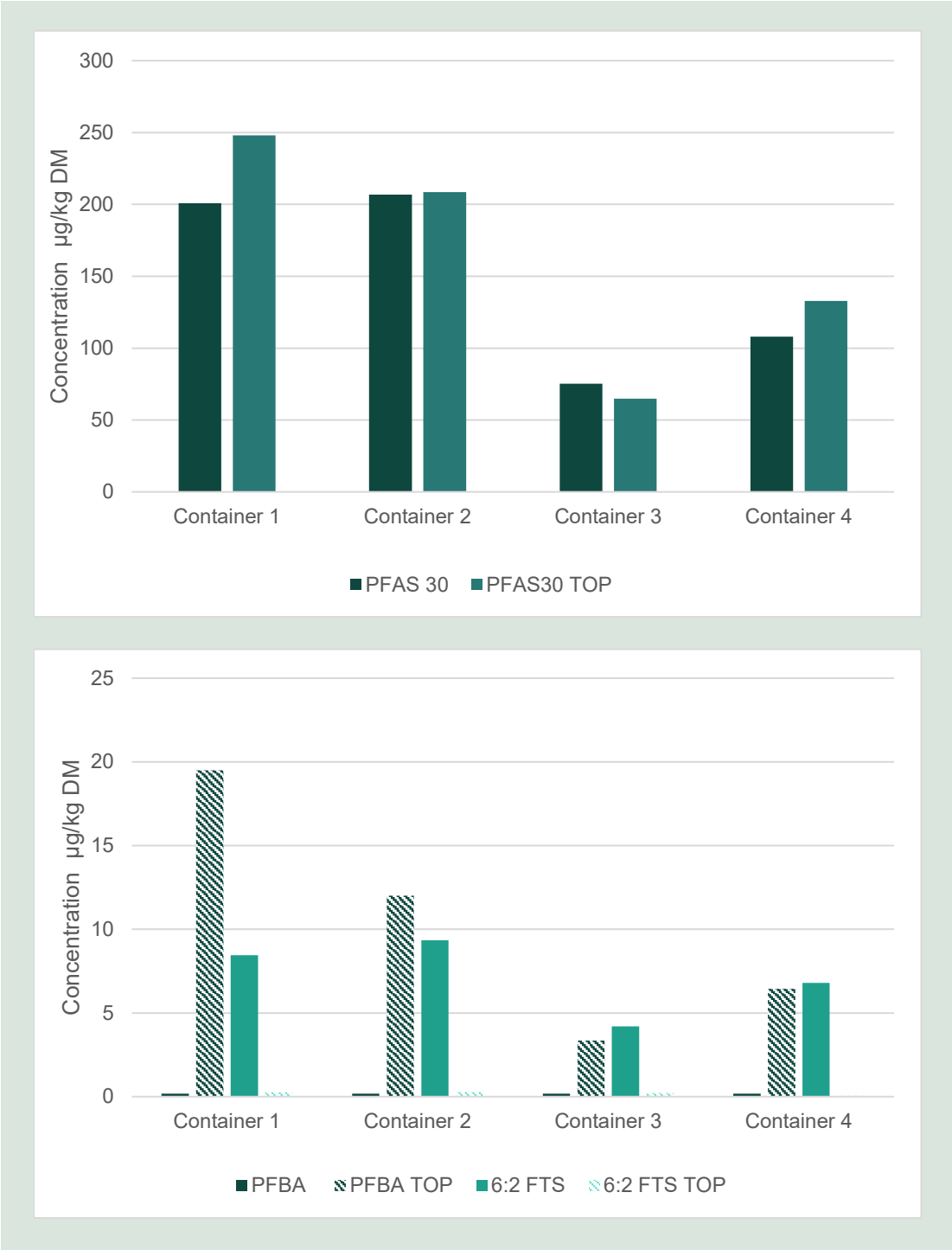


FIGURE 10. Comparison of baseline soil concentrations pre (filled bars) and post-TOP assay (striped bars) analysis. The very low/non detectable levels of 6:2 FTS post TOP confirm successful application of the TOP assay.

4.3 PFAS concentrations in soil after treatment

The tested technologies must be able to effectively clean the PFAS contaminated soil to below the Danish Environmental Protection Agency's quality criteria for soil of 10 µg/kg for PFAS Σ4 and 400 µg/kg for PFAS Σ22.

For both thermal methods assessed, the soil was heated to approximately 350–400 °C. Following thermal treatment, the container lid was removed to allow the soil to cool. After approximately 14 days, WSP collected soil samples for analysis beginning with the upper layers. Sequentially, each layer of soil was removed using an excavator, and additional samples were collected, ensuring representation from all depths within the container. In total, 72 soil samples were gathered and analysed. For further details, please consult the reports provided in Appendix 1 and 2.

An overview of all post treatment data for PFAS 22 is shown in Table 3 and for the mix samples that underwent TOP assay analysis in Table 4.

In the vast majority of the analysed soil samples, no content of PFAS has been detected. For the analytical programs applied, the detection levels were in ranges of 0.03-0.1 µg/kg. All samples that reached target temperature, in both pilot tests, had no detectable PFAS 22 post treatment. TOP assay results of samples reaching the target temperature did not show any detectable PFAS either. TOP assay becomes more uncertain when there is a lot of organic material, but this does not affect the results, as the organic material has also burned off.

Selected samples taken at cold points <350 °C did show some residual PFAS concentrations of mainly PFOS. The highest post treatment concentration for PFAS 4 in Krüger's pilot test was 2.1 µg/kg DM in a sample from a point below the target temperature of 350 °C (estimated temperature 250-300 °C from measurement on the outside of the heated box). The highest concentration in Arkil / Haemers pilot tests was 4.2 µg/kg DM PFAS 4, also observed at a cold point. The exact temperature at the cold point is not known, as there was no nearby censor.

Thus, the requirement of 10 µg/kg for 4 PFAS is met for all soil samples.

TABLE 3. Overview of PFAS concentrations in treated soil. Units in µg/kg DM. ND stands for non-detected.

	KRÜGER				ARKIL / HAEMERS - BATCH 1				ARKIL / HAEMERS BATCH 2
Sample id	1-33	34	35	36	1-4, 6,7, 10-18	8	9	5	All samples- (n=10)
Sample description	Sampled at or between measurement point inside box	Sampled at wall where lowest outside temp was measured (handheld instrument + one point logged for 2 weeks).			Random samples inside the container	Center line - 3 m from burners, ½ m below roof	Center line - ½ m from back end of container, ½ m below roof	Cold point - ½ m from back end of container	Random samples inside the container
Temperature	Target >= 350 °C	Below target 250-300 °C			Samples at target temperature	Samples at coldest points	Samples at coldest points	Samples at coldest points	Samples at and below target temperature but estimated above 350 °C
PFAS 4	ND	0,5	0,14	2	ND	0,27	4	0,14	ND
PFAS 22	ND	0,5	0,14	2,1	ND	0,27	4,2	0,14	ND
Specific compounds- above detection limit									
6:2 FTS	<0,03	<0,03	<0,03	0,061	<0,03	<0,03	0,082	<0,03	ND
PFBS	<0,03	<0,03	<0,03	0,05	<0,03	<0,03	<0,03	<0,03	ND
PFHxS	<0,03	0,055	0,042	0,27	<0,03	0,033	0,44	<0,03	ND
PFOS	<0,03	0,46	0,1	1,7	<0,03	0,24	3,6	0,14	ND
PFHpS	<0,03	<0,03	<0,03	<0,03	<0,03	<0,03	0,069	<0,03	ND

TABLE 4. Results for selected samples that were analysed for PFAS 30/35 and TOP Assay. All units in µg/kg DM. ND stands for non-detected.

	KRUGER			ARKIL / HAEMERS BATCH 1			ARKIL / HAEMERS BATCH 2
Sample id	Soil mix 1	Soil mix 2	Soil mix 3	Mix 1	Mix 2	Mix 3	2 mix samples
Sample description	>475 °C	350-475 °C	mix of samples 30,34,35,36	mix of 6,10,16	+ 21 +24 Cold point - 3 m from insertion end	2+20+23 Cold point - 2 m from insertion end	2 mix samples
Temperature	Target >= 350 °C	Target >= 350 °C	Below target 250-300 °C	Target >> 350 °C	Samples at coldest points	Samples at coldest points	Samples at coldest points
PFAS 4	-	-	0,58	ND	ND	ND	ND
PFAS 22	-	-	0,58	ND	ND	ND	ND
PFAS 30	ND	ND	0,58	ND	ND	ND	ND
PFAS 35	ND	ND	0,58	ND	ND	ND	ND
PFAS 30-TOP	ND	ND	0,42	ND	ND	ND	ND
Specific compounds- above detection limit							
PFHxS	ND	ND	0,083	ND	ND	ND	ND
PFOS	ND	ND	0,5	ND	ND	ND	ND
PFHxS after TOP	ND	ND	<0,1	ND	ND	ND	ND
PFOS after TOP	ND	ND	0,42	ND	ND	ND	ND

4.4 EOF analysis in soil before and after treatment

EOF analysis of the soil before treatment showed average values of 203-207 µg F /kg DM indicating an unidentified amount of organic fluoride in the soil. To clarify, PFOS contains only 65% fluorine by mass. This means that 100 µg/kg DM of PFOS would result in an EOF of 65 µg F/kg DM. Therefore, finding similar values for EOF and PFAS22 suggests that other fluorinated substances are present in the soil.

Post-treatment EOF analysis showed concentrations below the detection limit of 50 µg F/kg DM in Arkil/Haemers tests 1 and 2. In Krüger's samples heated above the target temperature, EOF concentrations were 89–90 µg F/kg DM. Overall, both thermal treatments substantially reduced organic fluorine in soil. The elevated EOF concentration of 277 µg F/kg DM in the Krüger sample heated only to 250–300°C may reflect transformation of organofluorine compounds into more extractable forms during heating.

TABLE 5 EOF concentrations in µg F/ kg DM.

Baseline (before treatment)	**Krüger (after treatment)**	**Krüger (after treatment)**	**Arkil/Haemers (post treatment)**
203-207	89-90	277	<50
Average of 3 composite samples	Average of 2 composite samples at target temperature >350°C	1 composite sample at 250-300°C (i.e. below target temperature)	3 composite samples from each batch

4.5 Desorption of PFAS from soil before and after treatment

To further document the effect of thermal treatment, single stage leaching tests (desorption tests with L/S 2/1) were performed in treated samples from the two pilot tests. Additionally, the same tests were performed in untreated soil.

Arkil / Haemers leaching tests of treated soil revealed traces of some PFAS 22. The highest concentration measured in Arkil /Haemers leaching tests is 6:2 FTS measured at 2.2 ng/L. Overall, the PFAS profile observed in soil leachate prior to heating corresponds with the condensate fingerprint obtained from the Arkil / Haemers container. Following the heating process, residual traces of the same compounds were identified in the eluate. Eurofins did not analyse for ultra short PFAS in the leaching tests from Arkil / Haemers.

Krüger also performed leaching tests of the untreated and treated soil and included ultra short PFAS in the analysis. PFAS 22 in the leachate from untreated soil was 23,000 ng/l of which 6,500 ng/l consisted of PFOS.TFA was present in the eluate from untreated soil in concentration up to 1,100 ng/l.

No PFAS 22 compounds were detected in the leachate post treatment, but increased levels of TFA and PFPrA were present, which might explain the extractable organic fluorine (EOF) above detection limit found in the post treatment soil from Krüger. TFA can form from degradation of PFOS (Weber et al., 2026). TFA can also form because of the thermal degradation of PFCA, as noted in the literature (Garavagno et al., 2024; Trang et al., 2022). Perhaps it can also be formed from thermal decomposition of PFSA, but we have not found references that show this.

PFPrA concentrations in the treated soil also increased, with could indicate that this is also a product of thermal degradation.

TABLE 6. Concentrations of PFAS in the eluat from leaching tests of untreated and treated soil.

	Krüger		Arkil/ Haemers	
Soil leachability test [ng/L]	**Untreated mix**	**Treated Soil mix 1 (> 475°C)**	**Untreated mix**	**Treated mix**
Ultra short PFAS				
TFMS	6.2	<1	Not analysed	Not analysed
TFA	1100	1700	Not analysed	Not analysed
PFES	<3	<3	Not analysed	Not analysed
PFPrA	<3	2500	Not analysed	Not analysed
PFPrS	<3	<3	Not analysed	Not analysed
PFAS 22				
PFBA	240	<1	93	1.2
PFBS	320	<1	130	0.99
PFPeA	2000	<1	640	0.53
PFPeS	570	<1	240	<0.3
PFHxA	1500	<1	600	1.7
PFHxS	5900	<0.5	3100	1.4
PFHpA	800	<1	340	0.31
PFHpS	420	<1	330	<0.3
PFOA	760	<0.5	380	1.1
PFOS	6500	<0.5	7300	1.7
6:2 FTS	4300	<1	3900	2.2
PFOSA	<10	<1	<10	<0.3
PFNA	50	<0.5	48	<0.3
PFNS	<10	<1	<10	<0.3
PFDA	<10	<1	<0.3	<0.3
PFDS	<10	<1	<10	<0.3
PFUnDA	<10	<1	<10	<0.3
PFUnDS	<10	<1	<10	<0.3
PFDoDA	<10	<1	<10	<0.3
PFDoDS	<10	<1	<10	<0.3
PFTrDA	<10	<1	<10	<1
PFTrDS	<10	<1	<10	<1
PFAS Σ4	13000	Not detected	11000	4.2
PFAS Σ22	23000	Not detected	17000	11

4.6 Non target screening (NTS) of PFAS in soil before and after treatment

Soil samples pre- and post-treatment from both pilot tests were also sent for non-target screening analyses. NTS analysis of pretreated samples confirmed the dominance of PFAS 22 and specifically PFOS. It is not possible to specify detection levels. A few other PFAS were identified in untreated samples, among which were weak signals Cl-PFOS (Perfluorooctane Sulfonate), FTSAm, PFSA, derivatives of PFECHS (Perfluoro(4-ethylcyclohexane) sulfonic acid), sulfonamides and pentafluorosulphanyle.

The NTS data from Arkil / Haemers showed no PFAS post treatment. The NTS data from Krüger's experiment post treatment showed no PFAS were detected in mixed samples that reached target temperatures (>350°C). Traces of PFOS, PFHpS and PFHxS (all among PFAS22) were found in the mixed sample of soil at a temperature of 250-300°C, which is below the target temperature. No other PFAS were identified in these samples.

In conclusion the results of NTS analysis confirmed to a large degree the results of the target PFAS analysis. For more detailed information refer to the Appendices from Eurofins in Appendix 1 and 2.

4.7 PFAS in gas phase and activated carbon

4.7.1 OTM 45 and OTM 50

As part of characterizing the waste streams OTM 45 and OTM 50 sampling was performed for both projects.

EPA Other Test Methods (OTM) 45 and 50 are specialized, performance-based methods developed to measure PFAS in air emissions from stationary sources (e.g., stacks). **OTM-45** measures semi volatile and particulate-bound PFAS, while **OTM-50** measures PFAS degradation products (volatile fluorinated compounds (VFCs)) using canister sampling. See box below for a short description of the two methods.

Short description of OTM 45 and OTM 50 methods

OTM-45 is a performance-based method applicable to the collection and quantitative analysis of specific semi volatile and condensable PFAS in air emissions from stationary sources, see otm-50-release-1-r1.pdf PFAS are collected by isokinetic extraction through a heated probe and heated filter. The flue gas is then led through a cooler, followed by collection of PFAS in condensate and on XAD-II columns. The equipment is rinsed with methanol after sampling is completed. The matrices were analysed for 32 PFAS (not accredited).

OTM-50 is a performance-based method applicable to the collection and quantitative analysis of specific volatile fluorinated compounds (VFCs). The target list originates from known industrial products and products of incomplete thermal destruction. Gaseous emissions samples collected by this meth-od are intended to be sampled from industrial source ducts, vents, stacks, etc.,otm-50-release-1-r1.pdf. VFCs are collected in a canister with a volume of 5 liters. The canister is evacuated to full vacuum before sampling. A partial gas stream is extracted from the duct via a heated probe and filter. The gas is led through 3 wash bottles with demineralized water, after which a smaller partial gas stream is extracted to the canister. If the water content in the gas stream is low, the wash bottles can be omitted. In the laboratory, the combined sample is typically analysed by GC/MS.

Eurofins, that performed the sampling and analysis of OTM 50 and OTM 45 for both vendors, note that the results are considered plausible, but with increased measurement and analysis uncertainty. No abnormal conditions were observed during measurement or analysis. OTM 50 was performed for the first time in Denmark during the pilot tests.

Results from these analyses are shown in Table 7 and discussed below.

TABLE 7. Fluorinated compounds detected in the gas phase of the Krüger and Arkil / Haemers pilot test at three different sampling points. Krüger's sampling occurred during the last part of the heat up phase. Arkil / Haemers' sampling took place a few days after leaving the dry-out phase at 100 °C in the cold point. Results marked with < and compounds not listed are below the detection limits. Results cannot be directly compared as ventilation rates varied. The unit is expressed in nanograms per normal cubic meter (Nm^3), that is, at 1 atm. and 0 °C.).

	KRÜGER			ARKIL/HAEMERS		
Compound	**Before DeFluorinator**	**After DeFluorinator**	**After carbon filter**	**Before Re-burn**	**After Re-burn**	**After Carbon filter (chimney)**
	Method OTM 45 - Unit ng/Nm³					
PFBA	0.29	< 0.08	< 0.09	0.16	<0.1	<0.1
PFPeA	0.16	< 0.08	< 0.09	<0.1	<0.1	<0.1
PFHxA	0.36	0.12	< 0.09	<0.1	<0.1	<0.1
PFHxS	0.14	< 0.08	< 0.09	<0.1	<0.1	<0.1
6:2 FTS	< 0.2	< 0.2	0.34	<0.4	<0.1	<0.3
	METHOD OTM 50 - unit ng/Nm³					
1H-perfluoropentane	<5800	<5400	110000	9700	<1500	<1500
1H-perfluorohexane	<1300	<1200	110000	3900	<830	<830
1H heptafluorpropane	<560	<520	<510	4300	<480	<480
1H-nonafluorbutane	<1400	<1300	<1300	4200	<1000	<1000
dodecafluoropentane	<2300	<2100	<2100	2300	<2000	2800
*Under field blind value. Only dodecafluoropentane was analyzed in field blanks.						

In Krügers project gas samples were colleted at three locations during the last part of the heating phase: outlet from the heated box, after the defluorinator, and following the GAC filter. The OTM 45 analysis revealed low amounts of 4 regulated PFAS in the outlet of the heated box, and only small traces of PFHxA after the defluorinator. Notably, the OTM 50 analysis showed high values of 1H-perfluoropentane and 1H-perfluorohexane after the GAC filter, along with minor concentrations of 6:2 FTS. Krüger suggested that this might result from sorption, accumulation, and subsequent desorption of these substances within the GAC filter. The GAC filter had been in operation for the entire dry out period until the defluorinator was put in operation when the amount of steam decreased.

Method OTM 50 also covers tetrafluoromethane (CF4), but it is not observed in the samples. It is the ultimate end product, possessing stability up to 1,400 degrees. OTM 50 relies on sample collection in a canister. If CF4 were present above the detection limit, it would be detected. It is not retained by carbon filters; therefore, any detection of CF4 requires its presence at the time of sampling.

CF4, as the final degradation product prior to mineralization, is described in the literature in the context of combustion - i.e., relatively rapid conversion in the gas phase at relatively high temperatures.

Degradation in contact with solid surfaces at lower temperatures over extended periods does not necessarily follow the same reaction pathways. It would be of interest to investigate this further. In laboratory experiments with PFAS concentrations high enough to allow for the establishment of a fluorine balance, extensive mineralization to fluoride is observed. However, these experiments did not include analysis for CF4; consequently, it is unknown whether CF4 is formed and escapes prior to mineralization.

Arkil / Haemers sampled the gas phase utilizing both OTM 50 and OTM 45 methods before reburn, after reburn and after the GAC filters. Traces of so regulated PFAS22 were found before reburn, consisting mainly of PFBA the only compound identified above detection limit of 0.16 ng/Nm^3 No PFAS were detected after reburn and downstream the GAC filter. Furthermore, NTS analysis of the GAC showed no traces of regulated PFAS.

Low levels of perfluorinated hydrocarbons, such as 1H-perfluoropentane and 1H-perfluorohexane, were detected prior to reburning in the Arkil/Haemers pilot test. Furthermore, dodecafluoropentane was detected before reburn at the concentrations equal to the detection limit.

There is a significant difference in the set-up of the two experiments. Krüger ventilated with a flow of 1 Nm3/h in 20 m3 of soil. Arkil / Haemers set up involves constant ventilation with a flow 20m3/hour in a smaller container. That means, when comparing the two methods, there is a 60-fold dilution factor. Gas samples from Arkil / Haemers experiment are 10-1000 times diluted.

1H-perfluoropentane and 1H-perfluorohexane were also observed prior to reburn in Arkil /Haemers pilot test. This indicates that, in the absence of a reburn step, these compounds can reach the activated carbon, remain there temporarily, and then be released. It is possible that this occurs in Krüger's pilot test, especially in the initial test period where the defluorinator was not functional, potentially resulting in a greater mass of these substances reaching the carbon filters where they can possibly accumulate and subsequently emitted. In the case of future full-scale projects, it is important that the defluorinator is functional from the beginning of the project to avoid the possibility of emitting fluorinated compounds to the atmosphere.

4.7.2 Emissions of HF

No detectable hydrogen fluoride (HF) was expected as initial PFAS concentrations indicated that HF production would be lower than the detection limit.

Krüger monitored the emission of HF weekly using Dräger tubes: No HF above the detection limit of 0.4 mg/m3 was detected in any of the three monitoring points (out of heated box, after defluorinator, after carbon filter).

Arkil did not measure HF as initial PFAS concentrations indicated that HF production would be lower than the detection limit of commercially available equipment. Due to considerably higher air flow per mass of soil.

HF is a significant occupational hazard. For future PFAS remediation projects, depending on the PFAS concentration levels in the soil, the possibility of HF generation needs to be accessed to ensure safe working conditions, depending on the set up. Denmark's current regulation (Bek. 1356 of 19-11-2025) sets indoor exposure limits at 0.8 mg/m³ for short-term and 0.4 mg/m³ for 8-hour exposure.

4.7.3 HRMS (High Resolution Mass Spectrometer)

Krüger employed a High-Resolution Mass Spectrometer (HRMS) detector for continuous monitoring of fluorinated compounds released from soil, as an alternative to the OTM-45 and OTM-50 methods. In practice, field deployment of the HRMS required substantial troubleshooting, and continuous monitoring was only feasible during limited periods. The selection of detectors was largely determined by practical considerations rather than optimal performance. Therefore, the HRMS detector provided little insight into the destruction process during thermal treatment. A snippet of the results is shown in the figure below. HF levels increased during drying and heating, reaching higher concentrations as temperatures approached the target, which indicates destruction of PFAS and not just volatilization. It is important to note that HF concentrations remained below 2,000 ppt or 0.002 mg/m^3 which explains why HF was not detected using the Dräger tubes having a DL of 0.4 mg/m^3.

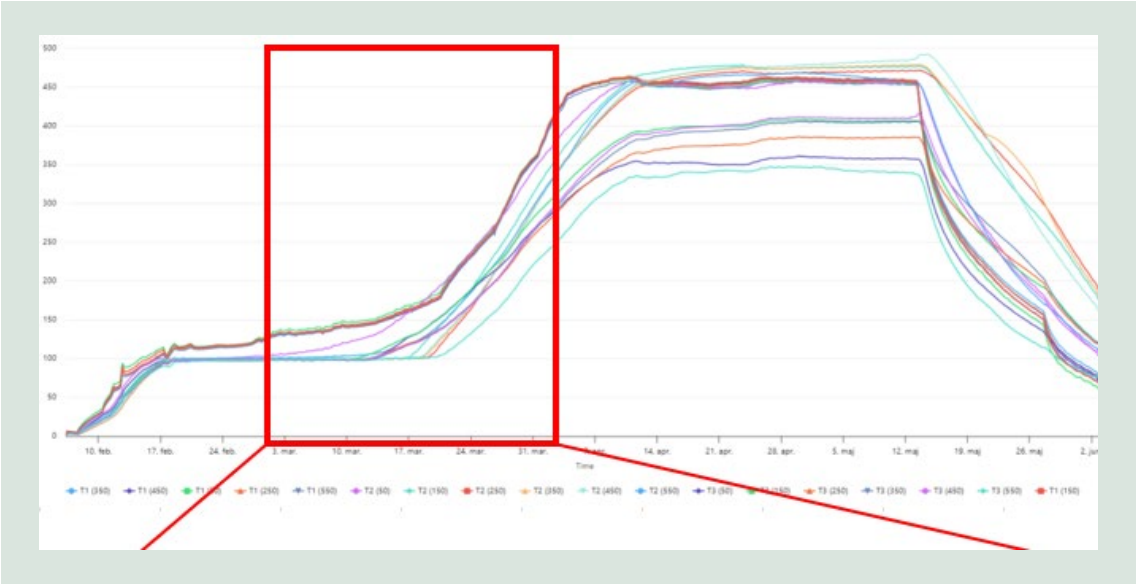


FIGURE 11. Temperature development (red box) and HRMS signals. HRMS signals, Source: Krügers report, appendix 2.

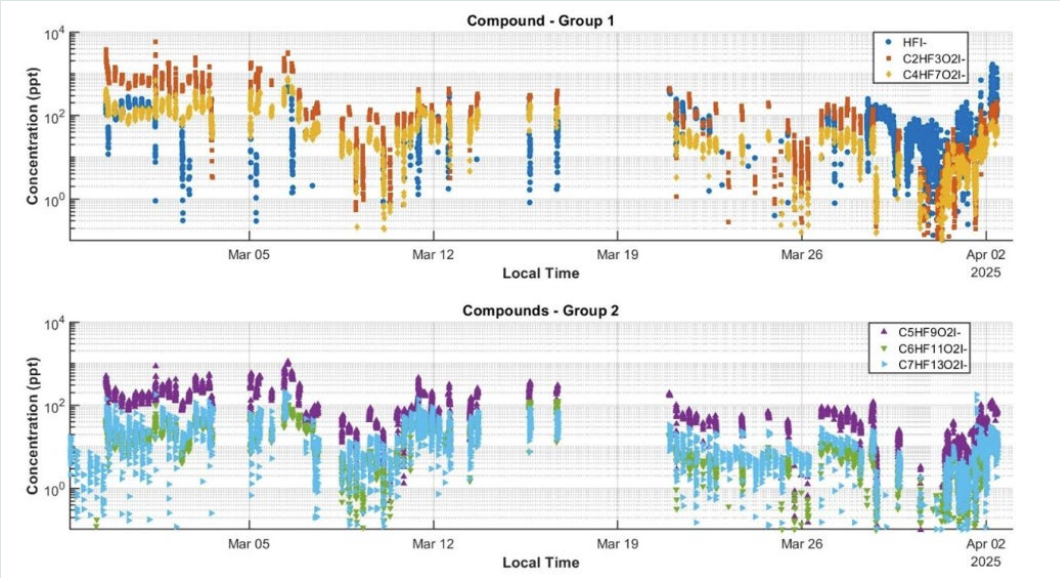


FIGURE 12. Concentrations of selected fluorinated species recorded during the dry out and heating to target treatment temperature phases. The signals are split into two graphs for improved readability with shorter chain PFAS (upper) and longer chain PFAS (lower). The dry out phase ends around March 25th. Due to instrument breakdown, the curves end one week prior to the OTM sampling.

The HRMS detector was not operational during OTM sampling. However, NTS analysis of OTM 45 extracts detected PFBS, PFPeS, PFHxS, that may align with the HRMS observations of C4–C6 PFAS. No PFAS were detected in NTS analyses post-defluorinator.

4.8 PFAS in other waste (condensate and sludge)

As part of heating the soil, water evaporates and is then condensed from air. Krüger's technology collects the condensate in tanks, while in Arkil/Haemers technology, the water vapors are diluted to prevent condensation, and therefore no condensate is expected. Monitoring of the condensate and any precipitate was required from both vendors.

4.8.1 KRÜGER

Krüger sampled the condensate sequentially during the dry out and heating phase which gives some insight to the desorption and outgassing processes for PFAS contaminants in the soil with increasing temperatures. Some interesting insights are available from the PFAS composition of condensate through the different phases of Krügers pilot test, as illustrated by Figure 13 and Table 8.

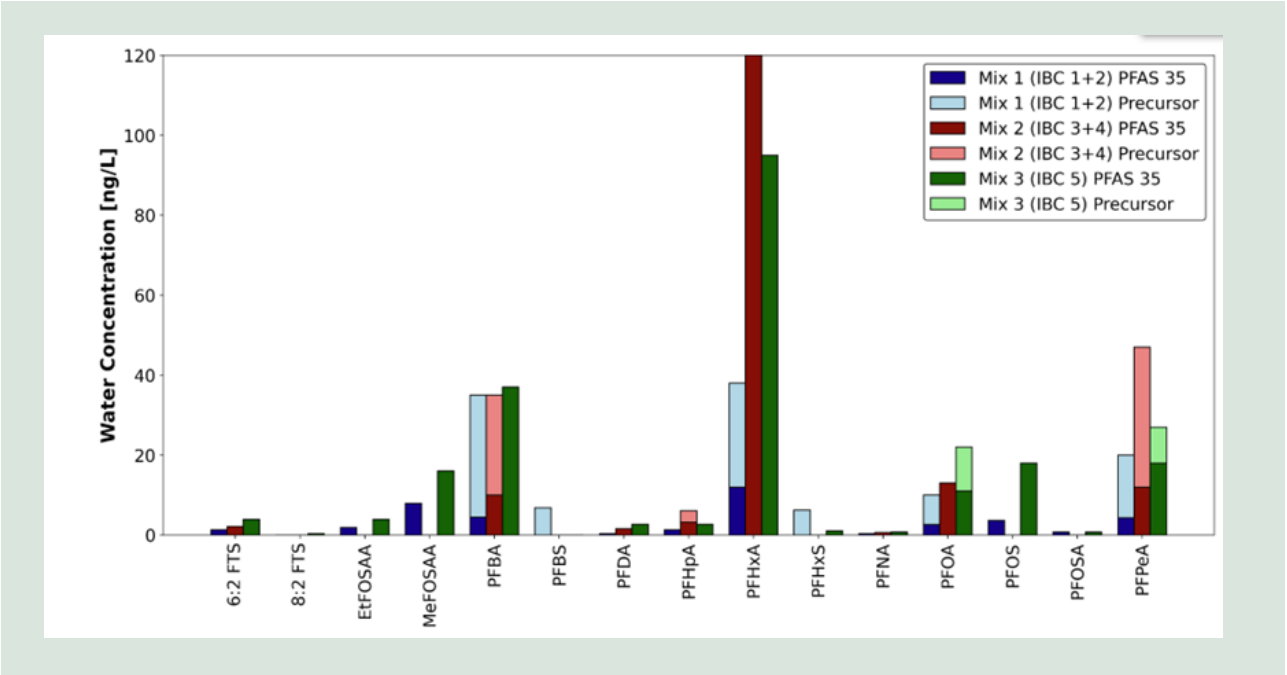


FIGURE 13. Detected concentrations of PFAS measured in ng/L, across three mixed water samples (mix 1, 2, and 3). Source: Krügers report. Mix 1 represents the initial dryout phase, mix 2 the late dry out phase and mix 3 from the heating period (from 100 °C to the target temperature)

More specifically:

- The concentration of PFHxA increases as the process moves from initial dry out (mix 1) to late dry out (mix 2) and stays high to the target temperature (mix 3). This suggests that PFHxA is either being formed, possibly from the thermal degradation of 6:2 FTS or other precursors and/or mobilized more efficiently at higher temperatures.
- PFBA and PFPeA also show increasing concentrations, particularly in Mix 3, indicating that these short-chain PFAS are either released or formed as byproducts during the heating and target temperature phases.
- Precursors are present in all phases, but their relative contribution varies. In most cases, precursor concentrations are like or higher than the measured PFAS, especially in the early phases.

TABLE 8. Concentrations (ng/l) of PFAS in the condensate throughout Krügers pilot test.

	Conden-sate tank 1 (IBC 1)	Condensate tank 2 (IBC 2)	Mix Tank 1 2 – TOP assay	Conden-sate tank 3 (IBC 3)	Conden-sate tank 4 (IBC 4)	Mix Tank 3 and 4 – TOP assay	Condensate tank 5 (IBC 5)	IBC 5 TOP as-say
Phase	**Initial dry out**			**Late dry out**			**Target temp**	
6:2 FTS	3.4	0.67	<3.0	2.5	3.1	<3.0	11	<3.0
PFBA	<0.6	0.72	*35*	<0.6	9.8	*35*	14	*35*
PFBS	<0.3	<0.3	*6.8*	<0.3	<0.3	<3.0	< 3	<3.0
PFDA	<0.3	0.41	*0.32*	1.4	1.7	<3.0	2.4	<3.0
PFDoDA	<0.3	<0.3	<3.0	0.5	<0.3	<3.0	<0.3	<3.0
PFDoDS	<1	<1	<10	<1	<1	<10	<1	<10
PFDS	<0.3	<0.3	<3.0	<0.3	<0.3	<3.0	<0.3	<3.0

PFHpA	1.4	1	*1.3*	1.9	3.6	*6.1*	< 3	<3.0
PFHpS	<0.3	<0.3	<3.0	<0.3	<0.3	<3.0	0.5	<3.0
PFHxA	3.7	32	*38*	70	110	*110*	97	*72*
PFHxS	<0.3	0.6	*6.2*	0.33	1.4	<3.0	0.98	<3.0
PFNA	0.45	0.31	<3.0	0.33	0.43	<3.0	0.57	<3.0
PFNS	<0.3	<0.3	<3.0	<0.3	<0.3	<3.0	<0.3	<3.0
PFOA	1.5	3	*10*	10	15	*13*	10	*22*
PFOS	13	0.38	<2.0	0.39	0.24	<2.0	25	*17*
PFOSA	<0.3	<0.3	<3.0	<0.3	<0.3	<3.0	<0.3	<3.0
PFPeA	4.1	6.6	*20*	14	14	*47*	14	*27*
PFPeS	<0.3	<0.3	<3.0	1.2	0.31	<3.0	<0.3	<3.0
PFTrDA	<1	<1	<3.0	<1	<1	<3.0	<1	<3.0
PFTrDS	<1	<1	<10	<1	<1	<10	<0.3	<10
PFUnDA	<0.3	<0.3	<3.0	<0.3	<0.3	<3.0	<0.3	<3.0
PFUnDS	<0.3	<0.3	<3.0	<0.3	<0.3	<3.0	<0.3	<3.0
PFAS4	15	4	16	11	17	13	37	39
PFAS22	28	46	118	103	160	211	175	173

The condensate sludge was analysed and found to be below the soil quality criterium. The analysis showed that the same PFAS were present in both the condensate and condensate sludge. Notably, PFDoDA was detected in the sludge at very low levels, even though being below the detection limit in the condensate, likely because it strongly adheres to particles.

Condensate from Krüger's pilot test was also analysed with NTS. NTS data from the condensate samples show quite different substance profile over time. The highest intensities are found during the late dry out phase, while very few substances are found at target temperature (see Krüger's report Figure 4.15 and Figures 4.12 and 4.13). It is remarkable that the non-target substances identified at the highest intensity in the condensate are not the same as the non-target substances found in the soil pretreatment, which indicates a degree of transformation of precursors at elevated temperatures, as also shown in bench scale studies.

4.8.2 ARKIL/HAEMERS

In Arkil/Haemers technology no condensate was expected. In the start-up phase of batch 1, a few liters of condensate were collected from purge valves due to unexpected operational issues. One sample underwent both PFAS and TOP-assay analyses. According to the results (see Table 9), there was an initial volatilization of 6:2 FTS and other pre-cursors, as the TOP tests showed concentrations five times higher than standard PFAS 35 measurements. Arkil / Haemers did not perform NTS analyses on the condensate. Additionally, since Arkil / Haemers did not observe notable precipitation in the limited condensate volume, no condensate sludge was sent for analysis.

TABLE 9. Concentrations of PFAS in condensate from Arkil/Haemers pilot test.

Parameter	Before TOP Assay	After TOP
	ng/l	ng/l
PFBA	68	510
PFPeA	51	670
PFHxA	110	850
PFHxS	3,6	<30
PFHpA	11	160
PFOA	11	<30
PFOS	17	<20
6:2 FTS	200	<30
PFNA	1,8	<30
PFDA	3	<30
Sum 4 PFAS	**33**	**0**
Sum 22 PFAS	**480**	**2200**

5. Sustainability

The objective of this chapter is not to give a complete LCA of the methods but focus more on certain elements in the process, primarily energy usage and equipment/consumables that are spent in the process and thereby generate a waste stream. In general, the overall equipment made of steel is reused in several sessions before being scrapped and reused as raw materials, thereby contributing relatively little to e.g. carbon footprint compared to the energy spent treating the soil.

In addition to the clear distinction that the Krüger pilot test utilizes electricity while the Arkil/Haemers pilot test employs gas as the energy source for heating, there are also notable differences in their respective approaches to soil treatment. Arkil/Haemers had the approach of reaching at least 1400 °C in the flame in their burners immediately to reach complete PFAS destruction in extracted vapors. Krüger used a heating strategy, focusing mainly on internal destruction of PFAS caused by catalytic high-temperature processes within the soil matrix. However, there was also evaporation followed by external catalytic decomposition. As explained in Section 4, both strategies ultimately proved to be effective.

Arkil/Haemers treated two soil batches in 54 days, while Krüger processed one batch in 100 days - about twice as long - but used less energy, as discussed in the next chapter.

5.1 Energy consumption

It has not been a goal to reduce energy consumption. The whole purpose of the pilot projects was to make a “proof of concept”, i.e. to be able to reduce the concentration in the soil and to demonstrate removal from the gas phase. Insulation is necessary only to be able to reach the target temperature but is in no way optimized in relation to reducing energy consumption.

Krügers box was insulated to U = 0.5 W/m^{2}K as a full-scale pile would be. Surface temperature during target temperature hold phase was 30 ºC.

Surface area to volume ratio is not good for the small boxes. Larger piles give less heat loss per ton. As a result, the measured consumption is significantly higher than would be expected in a full-sized treatment unit. Detailed information about the energy consumption of the treatment cells can be found in Appendix 1 and 2.

It should also be noted that since Arkil / Haemers has conducted pilot tests in two batches, where some treated soil is included again in batch 2, it is difficult to compare energy consumption with Krüger's pilot test, where all the soil is treated in 1 batch. But an attempt has been made to give an estimate of the energy consumption below.

Arkil/Haemers processed the soil in two batches, each using approximately 15 tons of soil. For these tests, they used about 6.5 m³ and 5 m³ of pressurized propane respectively - the smaller consumption of batch 2 was due to improved insulation in the treatment box and lower soil moisture because batch 2 contained soil from batch 1 to fill the container completely. This is also indicated by the temperature graph (figure 7), since batch 2 dries out much faster.

In total, 30.8 tons of soil were treated. The energy consumed for heating (and burning off/re-burning gases) was 77,451 kWh (3,064 Nm³ at 91,000 kJ/Nm³), resulting in an average energy usage of 2,515 kWh per ton of soil treated. Additional energy use for air ventilation, lighting, and similar needs added to another 9,400 kWh, bringing the overall average to 2,820 kWh per ton. This setup did not recycle exhaust energy, which, along with heat loss from the box, led to higher overall consumption. Arkil/Haemers estimated that nearly 60 % of the energy from the second batch was lost through burner exhaust gases.

Krüger processed the entire batch of soil - 31 tons - in a single operation, consuming approximately 55,000 kWh overall, which results in an average usage of 1,775 kWh per ton. Of this total, about 32,000 kWh was dedicated directly to heating, while the remainder supported ventilation, catalytic decomposition, instrumentation, lighting, and other auxiliary functions. Like the Arkil/Haemers test, a significant portion of energy in the Krüger test was lost as heat through the insulation into the surroundings. The energy consumption for handling the four pallet tanks with condensate is not included. The condensate was treated at the fire training site's local water treatment plant. So, the energy consumption for Krüger is slightly higher than this figure.

Both companies' visions for a full-scale project are that the thermal remediation should not be done in situ but that the soil should be excavated and treated in piles. Both companies have indicated that they expect a full-scale treatment system to require significantly less energy than was observed in this test case. Arkil/Haemers estimate that, under optimal conditions, energy consumption for heating alone could be approx. 350 kWh per ton.

Theoretically, the required energy is calculated to be about 160-170 kWh per ton for soil with 10% moisture (by weight) treated to 350 ºC. Depending on treatment temperature and moisture content this number changes. While reaching this lower value may be possible, considerable optimization is necessary. Krüger’s calculations suggest an expected value of around 360 kWh per ton. Therefore, after all essential optimizations, both techniques may achieve similar energy efficiency.

Overall, it is considered that Krüger's method is more energy efficient than Arkil / Haemer's method, because Arkil / Haemers has an energy loss in the air flow that goes out with the chimney. In relation to this issue, Arkil / Haemers has stated that on a full scale they want to use heat exchangers. They estimate that using air to air heat exchangers can reuse a large part of the energy.

Based on data presented at an ATV-meeting in November 2024 by Gorm Heron, large pilot treatment systems in piles in the USA (up to 1500 m³) have been successfully carried out with an energy consumption of around 450 kWh/m³. Assuming a density of 1,8 ton/m³ this corresponds to 250 kWh/ton which is even lower than expected from both Arkil/Haemers and Krüger.

In 2025, the average Danish carbon footprint for electricity was recorded at 123 g CO2/kWh. Regarding comments on CO2 equivalents in the form of the PFAS emitted during this incineration, this has been addressed in conclusion (chapter 6). Assuming an anticipated energy consumption of approximately 350 kWh/ton for both pilot tests, the estimated carbon footprint for the Krüger set-up is around 43 kg CO2 equivalents per ton of soil. For comparison, a household - a family with two adults and two children - uses approximately 4,500 kWh per year on average.

For the Arkil/Haemers set-up, which is projected to predominantly utilize natural gas as its primary energy source in a scaled-up scenario, the associated carbon footprint is approximately 200 g CO2/kWh, resulting in a total estimate of about 70 kg CO2 equivalents per ton of soil.

The carbon footprint can be lowered by using biogas from manure processing or using biogas generated from wastewater treatment, which has a low carbon footprint.

It is important to consider CO_2 equivalents in the form of PFAS substances that could potentially be released during incomplete combustion. This significantly influences which method emits the most CO_2 per kWh. For instance, 1H-perfluoropentane has a GWP of between 1,000 and 10,000, thereby having an impact on CO_2 emissions depending on the method used. It is difficult to determine which method would generate the lowest quantity of these high-GWP substances. Further work is needed to understand how these gases are formed and emitted.

5.2 Material consumption

In both setups, some materials were consumed, though not all of them may be necessary - or required to the same extent - in a full-scale application, based on test results.

For the Arkil/Haemers case, there were few consumables aside from the gas used. A backup GAC filter was installed to capture PFAS and other toxic compounds after the gases evaporated from the heated box underwent gas flame thermal combustion. This kind of filter would likely still be necessary as a safety measure in a larger system, but the GAC is expected to be reused multiple times since it is only activated if heating fails. Analyses detected no PFAS in the spent GAC or at the GAC filter's inlet. There will probably also be regulatory requirements for a back-up system. It will require more knowledge and more projects before it can possibly run without a back-up system.

Tubing within the system will need replacement after extended exposure to high temperatures, oxygen, and water, but this interval far exceeds the test run time.

In the Krüger pilot test, condensate had to be treated, which was managed by discharge to the on-site treatment plant constructed as a treatment train. If GAC filters were to be used, Krüger estimates that around 3 kg of GAC per ton of soil treated will be required in a full-scale operation. The carbon footprint associated with coconut-shell GAC optimized for PFAS adsorption has a carbon footprint of 1-2 g CO_2 per gram. Reactivated carbon has the lowest carbon footprint and can be used to lower the overall footprint. The catalytic mass used for gas-phase treatment should be reusable without further processing.

Like the Arkil/Haemers setup, most equipment is expected to be durable, withstanding many operational hours before being degraded by high temperatures, acids, or oxygen. Compared to the other expendables, lifetime is long and probably the least concern.

5.3 Other effects

A key aspect of the two pilot tests was to monitor the fate of fluorinated compounds. Nontarget analyses of treated soil showed almost no PFAS and very weak signals of other fluorinated components.

In both applications, hydrofluoric acid (HF) is expected to be one of the breakdown products. Assuming concentrations between 100–1,000 mg of PFAS 22 per ton and a fluorine content of about 60 %, this would equate to 60–600 mg HF per ton of soil if complete transformation occurs. The Danish B-value (the allowed maximum concentration contribution near a site's boundary) is 1 µg F/m³. Calculating the emission concentration is complicated, as it depends on both the temperature (and how quickly it rises) and the soil's ventilation rate. Ventilation is kept low in both methods to avoid losing heat from the soil. Krüger ventilates 0.05 /h (empty bed). Arkil / Haemers ventilates 2 /h (also empty bed). In the Arkil/Haemers setup, extra air is introduced both to fuel combustion and prior to GAC filters to control temperature, which

dilutes any produced HF compared to the Krüger setup. Krüger monitored HF levels during testing but observed no concentrations above their detection limit of 0.4 mg/m^3.

Other breakdown products were observed in especially the condensate and sludge (concentrations below the soil quality criterion) from the soil treatment in the Krüger setup.

Both Krüger and Arkil/Haemers observed fluorinated alkanes in the treated air above the detection limit of the sample but below the field blank value. It can be speculated whether these observations are real or some sort of artifact, since transport blinds also showed contents in the same range. However, it should be noted that the formation of these substances has been described in the literature, so it is quite likely that they are formed.

Local noise from filling and emptying treatment cells and potentially dust from especially emptying treatment cells is to be expected in the short periods when these activities take place. Both pilot tests operated at relatively low noise levels during the treatment phase itself. There was a complaint from a neighbour about noise from the fan, but it was quickly resolved.

The result of the treatment will be a sterilized soil product with low organic carbon content and low moisture. To restore its vitality, it is generally advisable to mix the treated soil with more fertile soil and add nutrients and water before reusing it as living soil. Alternatively, the end product could be combined with lime and used as a stabilizer in foundations beneath roads, among other applications. A challenge for biodiversity today is the lack of nutrient-poor soils where nettles, thistles and many grasses cannot grow, so perhaps "sterile" soil could be used for more than just filling under roads.

This approach would require a better understanding of the geotechnical properties of the material and may be worth investigating further. It should be noted that in Krüger's case, the part of the soil that was not oxidized and therefore must contain more carbon was just as pure as the oxidized part.

In previous thermal in-situ cleanups, it has been found that plants, etc. thrive after the cleanup is complete. Water and nutrients are added naturally – it just takes time. However, there is a big difference in the temperature to which the soil has been heated in relation to the biological potential. Both water, nutrients, etc. enter the soil over a long period of time. However, the fact that the soil has a low carbon content can be a barrier for many plant species and microorganisms at the beginning, just as the retention in relation to water also changes, which can also affect the species composition compared to untreated soil, i.e. it does not change the recommendation that if you want to use it as a growing medium, it is a good idea to mix some untreated soil/compost into the material.

6. Conclusion and lessons learned

Treatment efficiency
The pilot projects have shown that thermal remediation is efficient at treating PFAS in soil. Both pilot tests reached the target with no treated samples exceeding the Danish soil quality criteria of 10 µg/kg for the sum of PFAS 4 (PFOA, PFOS, PFNA and PFHxS).

The two pilot tests showed that soil samples treated at or above 350 °C had no detectable levels of the 22 PFAS compounds. Samples below target temperatures had residual concentrations of PFOS, PFHxS and 6:2 FTS of up to 3,6 µg/kg at the coldest point.

The two tested methods relied on thermal conductive heating (TCH) i.e. both methods involved heating steel pipes that distributed the heat into the soil volume, but there were some differences between the two methods, as different energy sources were used to heat the soil. Arkil / Haemers used gas (propane) and Krüger used electricity.

The management of the gases formed also differed for the two setups. In the pilot test by Arkil / Haemers the pollutant gases are mobilized by thermal desorption and are led to combustion in the flame. The contaminants were directed through the flame in the burner (1,400 °C) where it underwent mineralization through combustion.

Krüger use an approach where the main philosophy is to keep the vapors in the soil to enhance mineralization in the soil minimizing the output gases from the soil and treat the remaining in a catalytic deflourinator. The gases are held at 600°C for 15 minutes to mineralize volatilized PFAS. In the Krüger pilot test, condensate had to be treated, which was managed by discharge to the on-site treatment plant.

A key advantage of thermal remediation is that PFAS destruction is likely to occur, reducing or eliminating the need for post-treatment. In the Arkil/Haemers setup, this is achieved by reburning gases at high flame temperature, while Krüger uses a defluorinator. As a precaution, both pilot tests included backup air treatment using activated carbon filters. Further testing is needed to determine the evidence required to operate without carbon filtration. Because activated carbon is ineffective for ultra-short-chain PFAS, future projects should include monitoring of short-chain PFAS and fluorinated gases, such as perfluorohexane and perfluoropentane, to ensure that high-GWP gases are not emitted.

Both methods effectively cleaned PFAS-contaminated soil to below current thresholds, and extensive analysis suggests that PFAS was likely destroyed, though certainty is limited because the fluorine mass balance could not be established. This was due to the soil's high inorganic fluoride content relative to PFAS, with PFAS contributing only about 1% of total fluorine. Sampling and analytical uncertainties prevented accurate documentation of mineralization.

The most important lessons learned from the extensive monitoring program in these pilot tests are summarized below:

Comprehensive PFAS Quantification (PFAS 4, 22, 35, and TOP Assay):
Measuring the PFAS, as well as using the TOP (Total Oxidizable Precursor) assay, provided a robust understanding of both the initial contamination and the effectiveness of thermal remediation. The TOP assay revealed the presence and transformation of precursors, showing that most were already converted before treatment, but some additional PFBA and PFHxA were generated during the process.

Extractable Organic Fluorine (EOF) Analysis:
EOF analysis detected unidentified organofluorine compounds not found by targeted analysis. Post-treatment results confirmed significant organic fluorine removal, supporting PFAS findings.

Leaching (Desorption) Tests:
These tests confirmed that thermal treatment reduced the amount of leachable PFAS in the soil by 99,9 % - 100 %. PFAS-concentrations in soil below the soil quality criteria can still pose a risk to groundwater. Therefore, leaching tests are recommended for evaluating post-treatment PFAS mobility risks.

Non-Target Screening (NTS):
NTS analysis of soil before treatment demonstrates that compounds from the PFAS 22 group completely dominate the overall intensity, especially due to PFOS. NTS analyses identified few unidentified PFAS pre-treatment and none post-treatment, supporting the conclusion that thermal treatment was effective in destroying a broad range of PFAS. NTS is complex and time-consuming, often yielding results only after the treatment process is finished. While it provides valuable information, it's turnaround time limits its utility for real-time process control. While informative, NTS is resource-intensive and may be reserved for research or troubleshooting rather than routine monitoring.

As both pilot tests have now shown proof of PFAS destruction by thermal treatment, it is not necessary to include such analyses in future projects, for soils with similar PFAS fingerprints.

Air Emission Monitoring (OTM 45, OTM 50, HRMS):
Air emission monitoring using OTM 45, OTM 50 and HRMS provided insight into the fate of volatile and semi-volatile PFAS during treatment. The analyses confirmed destruction of the targeted PFAS but were costly and time-consuming. Because experience with thermal PFAS treatment remains limited, documenting contaminant levels in all waste streams is still valuable. Potent greenhouse gases, including 1H-perfluoropentane, were detected in air emissions. Further work is needed to understand how these gases are formed and emitted, and whether measures such as operating the defluorinator from the start of treatment are sufficient to prevent emissions.

Scalability of the methods
The two pilot tests showcased that the setups work as intended and the next step is to test in full scale. It is assessed that there are good opportunities for scaling up.

Arkil / Haemers points out in their report that a series of containers can be combined into a larger setup. Each container can operate as an independent thermal treatment unit, which can be replicated and deployed in parallel or series depending on site requirements. This design offers enhanced flexibility, easier maintenance, and seamless scalability. For larger projects

(>1,000 tonnes) it is more cost-effective to use prefabricated elements to construct a coherent chamber for the thermal remediation of contaminated soils. The advantage compared to prefabricated plug-and-play containers is using fewer materials, better use of energy through a more uniform distribution of energy and faster loading of soil with larger volumes.

Krüger points out in their report that in order to complete a thermal remediation at target temperature above 100°C, the groundwater must be excluded from the soil to be treated as any inflow of water will limit the temperature to 100°C, which is a likely scenario for in-situ application. This means that full scale thermal PFAS remediation of soil in Denmark is most likely to be performed by excavation and subsequent on-site thermal treatment in piles. The thermal in-pile treatment is scalable to considerable soil volumes. 45,000 m^3 piles treating dioxin contaminated soil have been operated by Krüger and TerraTherm jointly.

Krüger assesses that batch sizes of 5,000-10,000 m^3 are necessary to distribute fixed costs across sufficient volume to achieve competitive unit economics compared to conventional dig-and-haul solutions, which should be roughly 2,000 DKK/ton based on the Danish option of excavation and landfill disposal in Norway.

Both methods (Arkil / Haemers and Krüger) are in principle suitable for the same type of projects. Both methods could benefit from further development aimed at reducing energy consumption for large-scale applications. This project has not prioritized energy efficiency; instead, the main objective has been to see whether these methods can clean PFAS to levels below established soil quality standards.

A larger volume of soil is needed to reduce energy consumption because it is about having a ratio between heated soil and boundary. This is where we have the large temperature gradient. The energy consumption of large-scale projects is expected to be around 350 kWh/ton.

There are currently no full-scale treatment options in Denmark /3/. In future full-scale projects, it should be considered whether it would be appropriate to collect smaller batches of soil from several different locations at a central location where the thermal remediation is carried out. This would have the additional advantage of not having to seek necessary regulatory permits for each individual project.

When does it make sense to clean up soil by thermal remediation?
It is assessed that thermal treatment of PFAS contaminated soil is a suitable technology for hotspots where the soil is heavily contaminated. Heavily contaminated soil means concentrations that are higher than 10 times the soil quality criteria, i.e. over 4,000 µg/kg for PFAS Σ22 and / or over 100 µg/kg for the PFAS Σ4.

Currently, there is uncertainty regarding whether soil with PFAS concentrations below the soil quality criteria might still pose a risk to groundwater. As a result, there may be an incentive to also treat soil with lower concentrations to mitigate potential impacts on water abstraction and land use. In Denmark, up to 15,000 locations have been identified where activities may have led to PFAS contamination of the soil /4/.
Previous full-scale thermal remediation projects of chlorinated solvents and other substance groups show that thermal remediation is suitable for both sandy sediment and clayey soils. This is also considered to be the case regarding PFAS.

The competitiveness of thermal treatment relative to soil washing for sandy sediments has not yet been evaluated. However, for clay-rich soils, where soil washing is not an appropriate option, remediation through thermal methods presents a viable solution due to its applicability across all soil types.

This approach is considered more sustainable than alternatives such as transporting contaminated soil to Norway for landfilling, as it allows for local treatment. Furthermore, thermal remediation is likely to destroy PFAS compounds, effectively removing these persistent substances from environmental circulation.

In addition to remediation of PFAS contaminated soil, thermal methods will probably also be a good solution for the remediation of PFAS contaminated sludge or PFAS contaminated filter cake after soil washing, but it is not investigated in this project. Also, thermal treatment is relevant to consider for soils contaminated with a mixture of contaminants.

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Appendix 1. Reports from technology suppliers

Appendix 1.1 **Arkil / Haemers – Thermal desorption for PFAS removal and high-temperature destruction, December 2025**

Appendix 1.2 **Krüger (Veolia) – Pilot scale thermal PFAS soil remediation test, March 2026**

Resume

The Danish Environmental Protection Agency has funded the implementation of pilot tests for demonstration of thermal remediation of PFAS contaminated soil. The demonstration projects have been anchored in the Capital Region of Denmark.

Two thermal methods have been tested. Both projects demonstrated that Thermal Conductive Heating (TCH) effectively remediates PFAS in soil. All treated samples met the Danish soil quality criteria. Soil heated to at least 350°C showed no detectable PFAS compounds, while samples heated to 250–300°C retained low residual concentrations. A target temperature of 350°C is therefore recommended.

The two methods used different energy sources and gas management approaches. Both are likely to destroy PFAS, reducing the need for post-treatment.

Both methods are considered ready for full-scale testing. In Denmark, treatment will likely involve excavating soil and treating it on-site in piles. To achieve economic competitiveness with conventional disposal, batch sizes exceeding 1,000 tonnes are required.

Thermal treatment is particularly suitable for PFAS hotspots and clayey soils, where soil washing is unsuitable. It may also offer a more sustainable alternative to landfilling by destroying PFAS rather than relocating the contamination. However, treating all lightly contaminated soil thermally is unrealistic given the large number of potentially affected sites in Denmark.

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