EPA Superfund Program – Technical Bulletin 2026-01

Considerations for In Situ Application of Colloidal Activated Carbon at PFAS-Contaminated Groundwater Sites

The EPA's Superfund Program has developed this technical bulletin to guide Remedial Project Managers (RPMs) and technical support staff in evaluating the use of colloidal activated carbon (CAC) to address per- and polyfluorinated substances (PFAS) contamination in groundwater on a site-specific basis. This Bulletin is rooted in existing guidance and identifies best practices based on a review of the literature.

PFAS, widely used since the 1950s, pose complex challenges due to their persistence and co-occurrence with legacy industrial pollutants. CAC, traditionally used for groundwater treatment to remove organic contaminants, is being proposed as an in-situ sorption barrier for PFAS in groundwater at some sites.

While the use of CAC in mitigating chlorinated solvent migration in groundwater via adsorption has been demonstrated (EPA, 2018), the long-term effectiveness of CAC in mitigating PFAS plume migration is still a topic of research.

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Purpose

The purpose of this document is to assist United States Environmental Protection Agency (EPA) Remedial Project Managers (RPMs) and technical support staff with understanding the applications and considerations in the use of colloidal activated carbon (CAC) to address PFAS contamination in groundwater on a site-specific basis. This is important because at many sites there is an urgent need to reduce PFAS plume migration. Although the science is rapidly evolving, it is useful to summarize what is known about the implementation of CAC in various scenarios. This Technical Bulletin outlines important considerations for evaluating the utility of CAC in addressing PFAS migration in groundwater and best

practices based on the current science and understanding. This document will be updated to reflect the best science as additional information becomes available.

Assumptions and Limitations

The discussion and recommendations herein are most relevant to PFAS detected in groundwater flowing through unconsolidated aquifer matrices. CAC applications to fractured bedrock and unsaturated soil, and associated considerations, are not specifically discussed.

Key Considerations in Remedy Selection

CERCLA requires that remedies are protective, cost effective, and meet certain federal and state requirements. CERCLA has a preference for permanent treatment. To the maximum extent practicable, sites should utilize alternative treatment technologies. The NCP and existing guidance provide further direction on how to achieve those CERCLA requirements and goals.

Relevant here, existing guidance on the use of CAC for groundwater remediation is presented in EPA's Remedial Technology Fact Sheet – Activated Carbon-Based Technology for In Situ Remediation (EPA, 2018).[1] The fact sheet presents CAC for chlorinated volatile organic carbon compounds (cVOCs) and petroleum hydrocarbons but does not discuss CAC for PFAS. The use of CAC to sequester PFAS in groundwater is an innovative technology and has yet to be effectively demonstrated as a long-term remedy. To date, the technology has been applied primarily at Federal Facility Superfund sites early in the Superfund process in the form of bench or pilot studies (e.g., SERDP-ESTCP program), which is in line with Part 300.430(d)(1) of the NCP: "Bench- or pilot-scale treatability studies shall be conducted, when appropriate and practicable, to provide additional data for the detailed analysis and to support engineering design of remedial alternatives."

In light of these considerations, several site-specific questions should be addressed prior to considering CAC as a remedy or as a component of the overarching site remedial strategy.

- Are the aquifer characteristics compatible for a CAC remedy?
- Are there co-contaminants, like other VOCs, or dissolved organic carbon (DOC) that would compete for sorption sites on the CAC barrier?
- Are there short-chain PFAS (i.e., PFAS containing 6 or fewer carbon atoms)? Short-chain PFAS are less strongly adsorbed to CAC than long-chain PFAS; see discussion below.
- Are there alkaline or high ionic strength conditions that could affect the sequestration of PFAS by CAC?
- How long will the injected CAC volume sequester PFAS and when can contaminant breakthrough be expected? How will this be determined?

Consistent with all innovative remedial technology applications, site specific hydrogeologic and geochemical characterization followed by bench-scale testing and pilot testing are steps that RPMs and technical support staff might consider prior to evaluating CAC in a feasibility study (NCP Part 300.430(d)(1)). The above questions may be useful starting points for Data Quality Objectives (DQOs) in a study design.

What is CAC and how does it work?

CAC is derived from activated carbon, which is the result of organic material being "activated" by pyrolysis at high temperature with or without chemical additions. The result is a low-density granular carbon

material with high surface area, which is useful for filtration/adsorption. Activated carbon can be further ground to a lower particle size to form CAC, which is injected into the saturated zone as a slurry or can be mixed or trenched into the saturated zone using heavy equipment. The main purpose of CAC for addressing PFAS in groundwater is to intercept and mitigate migration of PFAS contamination. CAC is an in situ technology applied to the aquifer where contaminants are present, creating a barrier (or barriers) that capture the dissolved contaminants. In theory, this temporarily decreases or prevents the migration of contaminants downgradient towards vulnerable receptors, including drinking water wells and/or releases to surface water.

Carbon particles in CAC are smaller than that of granular activated carbon (GAC), commonly used in drinking water treatment (1-2 microns diameter on average compared to 1 mm), which gives a higher surface area to volume ratio for increased adsorption sites. Organic contaminants, such as PFAS, will adsorb to the carbon particles. If there are other organic contaminants besides PFAS, they may preferentially adsorb to the carbon particles, displacing PFAS. Unlike the ex situ use of activated carbon (such as GAC cannisters), in the in situ application of colloidal activated carbon (CAC), the carbon cannot be changed out once it has been injected. As sorption sites are filled, and/or groundwater concentrations decrease, previously adsorbed compounds can also begin to desorb, re-releasing contaminants into the groundwater as the CAC reaches an equilibrium with current water quality conditions. The most common remedial response to CAC breakthrough is reinjection. Under these conditions, waste could be left in place, which would require 5-year reviews. However, if shallow enough, the CAC may also be excavated and disposed of at a licensed facility.

The technology has been applied to VOC plumes successfully, and the ability of the CAC to retard the movement of VOCs long enough for biodegradation to occur has been well documented (EPA, 2018).[1] While injectable CAC was developed to both immobilize and destroy (with the aid of various amendments) chemical contaminants, such as petroleum hydrocarbons and chlorinated solvents, current iterations of CAC are not capable of destroying PFAS. This distinction may be important when considering how CAC aligns with the NCP preference for remedies that provide long-term effectiveness and permanence. Despite this limitation, CAC may have utility in mitigating the migration of PFAS. The technology has been studied at the bench scale and pilot tested in the field on PFAS plumes.[2] The mechanism of contaminant immobilization is generally understood to be adsorption, primarily through hydrophobic and electrostatic interactions. Through these processes, long-chain PFAS (e.g., PFOA, PFOS, PFOSA, and PFNA) will be more effectively retarded compared to short-chain PFAS (e.g., PFBA, GenX and PFBS). Consequently, because the PFAS retardation mechanism is currently understood to be governed by adsorption (i.e., non-destructive treatment), this type of intervention will have a limited effectiveness based on the available sorption sites and competition for those sites. Once the CAC has been fully loaded with PFAS and other adsorbed molecules, shorter chain PFAS will likely be displaced from the CAC sorption sites by longer-chain PFAS, and eventually long chain PFAS breakthrough may occur once sorption capacity is exhausted. Longevity of CAC effectiveness (i.e., until breakthrough occurs) in the subsurface is expected to be related to the mass of CAC emplaced in the subsurface; contaminant loading or flux (concentration × groundwater velocity); CAC interactions with the groundwater matrix; installation and design performance; and overall hydraulic control. Similar to all in situ groundwater remedies, understanding site geohydrology, groundwater geochemistry, and contaminant distribution will maximize the chance of developing an effective remedial design. Also, development of effective monitoring networks is critical for evaluating performance.

In Situ CAC Advantages

- Applied within groundwater plumes or near plume margins, CAC may reduce the transport of PFAS downgradient towards potential receptors.
- Applied at the source, CAC may reduce mass flux from the source area.
- CAC may be used as an interim remedy and/or in conjunction with other remedial components (e.g., in situ CAC may be installed to prevent plume migration towards receptors while extension of a public water line is occurring).
- CAC may retain co-contaminants like cVOCs and PAHs.[1] In some cases, the destruction of these co-contaminants may also occur with the addition of a reactive medium like zero-valent iron, though the reactive medium's effect on PFAS would require additional study.
- In situ CAC treatment zones designed to intercept groundwater flow pathways have a low energy footprint since no groundwater pumping is needed.
- CAC injections can be customized to the plume configuration, i.e., adding more CAC where contaminant concentration is highest and groundwater flow or mass flux is greatest.
- CAC is based on a well-established treatment technology (GAC).
- The strategy for monitoring performance can be simple. It is similar to monitoring used for other in situ treatment zones, such as permeable reactive barriers.
- Though there is no destruction of PFAS in a CAC barrier, there are low operation and maintenance costs compared to a pump and treat system, for instance.

Efficacy and Longevity

An important question is how long CAC can maintain its efficacy. CAC injection aims to retain contaminants from ten years to multiple decades,[2] but there are a number of factors that contribute to efficacy and longevity, including:

- The size of activated carbon particles affects their specific surface area and adsorptive properties.
- Particle size can also impact hydraulic conductivity in the subsurface, potentially clogging pore throats in unconsolidated aquifer materials, and thereby impacting groundwater flow velocity and direction.
- PFAS types (perfluorocarboxylic acids [PFCAs] vs perfluorosulfonic acids [PFSAs]) vary in sorption affinity; PFSAs, like PFOS, are more strongly adsorbed than PFCAs of equivalent chain length, like PFOA —additionally short chain PFAS sorb less than long chain PFAS.
- Site groundwater geochemistry including pH, total dissolved solutes, cations, anions, organic carbon, may impact dosing of CAC.[3] Early applications of CAC based dosing solely on contaminant concentrations measured in the monitoring wells resulted in underdosing and ineffective contaminant removal.[4,5] (see Technical Considerations section bullet 2). Organic carbon, naturally present in groundwater or other contaminants at Superfund sites can compete with PFAS for sorption sites.[6]
- Effective distribution of the CAC may be challenging in some lithologies. Heterogeneity can preferentially direct CAC into more permeable strata. Sites can overcome this issue with high pressure injection, or with deep soil mixing.[7] Delivery into particularly high conductivity zones may result in considerable displacement of CAC; $CaCl_2$ can be applied to halt the migration of CAC.[8] Injection pressure must be tailored to match project objectives and minimize the potential for unwanted fracturing of low-permeability formations, resulting in either development of new preferential pathways or loss of CAC within fractures that later collapse.
- Natural biodegradation of perfluorosulfonic acids over time may create daughter PFAS products that have a lower sorption affinity.[9] Similarly, adding an ISCO remedy, depending on the amendments (see ISCO bulletin), can reduce the sorption affinity of co-mingled PFAS.

- Design considerations should account for maximum flux zones, i.e., where the groundwater velocity × ΣPFAS concentration is the greatest; high contaminant flux zones will typically dictate where breakthrough first occurs.
- Often, practitioners will suggest a follow-up application of CAC if the first application is insufficient for site treatment goals.

RPMs can consult with technical staff from headquarters or the regions to understand potential implications of these factors on their sites.

Impact of Co-contaminants

It can be difficult to predict how co-contaminants might affect PFAS adsorption by CAC given the large number of factors pertaining to the environment, contaminant concentrations and PFAS chain length that can vary across and within sites.[10] For example, one study tested the impact of TCE, 1,4-dioxane, ethanol, and diethylene glycol butyl ether (DGBE) on PFAS sorption to CAC.[11] Of the four potential co-contaminants, DGBE resulted in significant suppression of PFOA and PFOS adsorption, while TCE and benzene reduced only PFOS adsorption. There was no significant effect on PFAS sorption by 1,4-dioxane. NAPLs have been shown to have a varying effect on PFAS sorption, depending on PFAS chain length and matrix carbon concentrations.

Technical Considerations

As with most remedial technologies it is important to acknowledge that there are limitations, and because CAC is an emerging technology, there are also data gaps on its long-term contributions to remedial effectiveness. At present, below are the technical considerations that RPMs should keep in mind when evaluating CAC technology.

Site Characterization and Plume Characteristics

- **Application of CAC requires an in-depth understanding of the Conceptual Site Model (CSM) and the underlying site hydrology**. Due to the unique properties of PFAS and complexities of individual site hydrology, utilization of CAC requires an in-depth understanding of the CSM and targeted site characterization to understand groundwater flow, porosity and permeability of the injection area, preferential flow pathways and groundwater geochemistry.
- **CAC effectiveness may be heavily influenced by CAC properties, PFAS structure and groundwater chemistry**. Because there are many PFAS compounds with varying chemical structures, the effectiveness of CAC is likely to be dependent on the chemical structure of each PFAS compound and the mixture of PFAS present in the groundwater. There are constant competing electrostatic and hydrophobic interactions between PFAS and environmental media.[12] Additionally, the ionic properties of PFAS and soil substrates have been shown to have an effect on their environmental behavior.[6,13] Consequently, the fate and transport of PFAS is more dependent on changes in pH, presence of polyvalent cations and charged substrates like clay than many other environmental contaminants. For this reason, utilization of CAC to address PFAS will be heavily influenced by site properties such as geochemistry, the individual PFAS compounds present at the site, and any potential variations in the application or properties of the CAC being applied.
- **Shorter Chain PFAS breakthrough CAC more quickly than longer chain PFAS.** PFAS chain length has been shown to heavily influence its mobility in the environment.[14] Longer chain PFAS are more readily adsorbed to activated carbon substrates, than shorter chain PFAS.[15] Adsorption of PFAS onto traditional activated carbon substrates has also been shown to be dependent on particle size and PFAS structure. Additionally, PFAS concentration and subsequent micelle formation in interfaces can be expected to influence adsorption onto activated carbon substrates. In other

words, adsorption may be concentration-dependent at many groundwater sites. Similar observations can be expected in adsorption of PFAS onto CAC substrates. For these reasons the available surface area of CAC, PFAS carbon chain length and PFAS concentration are likely to have significant impact on the ability of CAC to absorb PFAS.

- **Applicability**. CAC may be best used for PFAS plumes up to a depth where injection pressures do not fracture the aquifer. A record of the precise location of its application is required. Because waste is being left in place the implications for future restoration and long-term monitoring requirements must be considered. If the CAC is unable to stabilize a significant fraction of the regulated PFAS over the long term in a drinking water aquifer, a waste management area (WMA) designation may be required. If the area outside the WMA is unable to reach ARARs, then a Technical Impracticability waiver or alternative treatment approach for that portion of the site would need to be considered.

Design/Installation/Emplacement

- **Application of CAC may be an iterative process and may lead to other impacts at the site**. Because binding of PFAS to CAC is reversable, additional applications of the CAC may be necessary if concentrations downgradient are not meeting site goals. Bound PFAS may also subsequently desorb if groundwater concentrations decrease or if competing contaminants bind to CAC. Application of any injectable has the potential to alter subsurface hydraulic conditions causing groundwater and plume flow patterns to shift. Injection wells may be damaged in the process and may require re-development.
- **CAC has a limited lifetime.** CAC, like GAC, is expected to have a limited lifetime and PFAS are expected to be remobilized in the future (see section "Efficacy and Longevity"). For this reason, reapplication of CAC may be necessary, and CAC may be best applied in conjunction with other remedial technologies where concentrations of PFAS are elevated.
- **Installation**. CAC may be suitable as a barrier and is often placed by a property boundary or between the source and a receptor. There should be space on the downgradient side to monitor for breakthrough and bypass. $CaCl_2$ can be injected at downgradient locations to limit CAC advancement and washout through the porous media. In addition to CAC injection, some sites are employing a funnel-and-gate configuration to ensure groundwater flow is directed into the CAC treatment zone and to prevent by-pass. Tree roots, abandoned borings/wells, or soil fractures in low permeability soil can cause daylighting (discharging to the surface). Drilling contractors should be familiar with the injection process to avoid daylighting of the product, inadvertent fracking, and other distribution issues. If any of these occur during injection, pause and adjust the injection plan.
- **PFAS will remain onsite**. Because CAC is not a destruction method for PFAS, PFAS will be temporarily sequestered with the potential to release and must be adequately monitored for breakthrough. The creation of a waste management area must be considered for a site's long-term management.

Monitoring Performance

To date, there is no EPA guidance or protocol for the validation of in situ CAC performance. Careful consideration should be given to the development of project specific Quality Assurance Project Plans and sampling/monitoring plans that include ongoing monitoring to evaluate temporal conditions and confirm CAC applications have achieved their intended purpose and are not re-releasing PFAS into the environment. With waste left in place, performance monitoring and remedy review will be required indefinitely.

Elements of a performance monitoring plan should include regular groundwater sampling (i.e., quarterly

but monitoring frequency can be informed by site-specific conditions and performance results) from monitoring wells installed on the upgradient and downgradient sides of the in-situ treatment zone. Monitoring wells located within the treatment zone may also be desired. Side gradient wells should be placed to evaluate whether there is plume bypass around the edges of the treatment zone. Placing wells along transects, i.e., along inferred groundwater flow paths is the common practice for evaluating in situ reactive barriers. The location of the performance monitoring network should be developed with site-specific considerations in mind; for example, downgradient monitoring wells should be located close enough to the injection zone such that the effects of sorption in the CAC zone are observed; this will depend in part on the average seepage velocity at the site.

Groundwater levels should be monitored, perhaps using a series of in-well devices to record high-resolution water level changes (to evaluate potential mounding or re-routing of groundwater flow). Groundwater samples should be collected for PFAS analysis and other specific contaminants of concern. Consider also monitoring standard geochemical parameters (pH, specific conductance, oxidation-reduction potential, dissolved oxygen, turbidity, total dissolved solids), and major ion chemistry of groundwater (including calcium, magnesium, potassium, sodium, iron, manganese, chloride, sulfate, bicarbonate, and organic carbon). Other constituents could be added based on site-specific considerations.

Contingency Planning

- Since breakthrough is a concern, develop a contingency plan for additional injections, a pump-and-treat system, or other remedial methods.
- A commonly encountered issue is underdosing the CAC and the need for additional injections. This may be due to excessive constituents competing for sorption capacity, or groundwater elevation changes that mobilize additional contamination in the vadose zone. RPMs should plan for the possibility of more than one injection.
- Some applications of CAC have led to daylighting of groundwater as a treatment area clogs with precipitate or biofilm. If this occurs, excavation and reinstallation with higher permeability material should be considered.
- Anaerobic conditions may develop in the application area and if aquifer constituents are amenable to biodegradation, methane may be produced. Therefore, methane in groundwater may need to be monitored if buildings are nearby.

CAC Use at NPL Sites

Various pilot studies are underway at CERCLA sites including Alameda Naval Air Station NPL Site, US Army Camp Grayling NPL, Eielson Air Force Base, Naval Auxiliary Landing Field Fentress and numerous other sites managed outside of EPA. Coordination and feedback with individual site managers on the effectiveness of CAC at those sites may aid in understanding whether CAC is an effective option for other sites.

Policy Considerations

CAC can retard PFAS migration in the groundwater but does not destroy PFAS. As a result, PFAS remains in place, which has policy implications under CERCLA. Consult with your regional management and headquarters or regional policy advisor for direction.

Consideration of Other Options and Combining CAC with other Treatment Techniques

It may be useful to consider other treatment technologies in conjunction with CAC or in lieu of CAC.

Researchers at EPA have tested a combination of CAC with in-situ solidification to reduce the leachability of PFAS leading to promising results.[16]

Zero-valent iron (ZVI, ISCR), ISCO, and/or bio-augmentation is often added to the CAC injection to address co-contaminants such as cVOCs. Added injectants need to be evaluated to ensure there will be no detrimental effects on PFAS (i.e., potential transformation of precursor PFAS into terminal PFAS with the addition of oxidants).

Actions and Options for EPA RPMs

- **Seek Technical Assistance**
  Engage your regional hydrogeologist and chemist to assist with the review of documents (QAPPs, sampling and analysis plans, design documents, monitoring results, etc.). If additional scientific expertise is needed, contact the OASES Technical Support Branch in the Environmental Solutions Division OASES_SF_TSC@epa.gov. Groundwater Forum or Federal Facility Forum PFAS work group members are also helpful in providing advice based on experiences at other sites. Depending on your site type and conditions, additional technical expertise may be helpful.
- **Seek Policy Input**
  Coordinate with your regional management for policy input. With your manager, you may engage with OLEM OSEM.

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