

Understanding PFAS Remediation Using Colloidal Activated Carbon



Understanding *In Situ* PFAS Remediation Using Colloidal Activated Carbon

For many years, activated carbon has played a pivotal role in cleaning contaminated sites, serving as a medium to filter pollutants from groundwater extracted by mechanical pump-and-treat systems. Recently, scientists and engineers have developed advanced technologies to effectively apply micron-scale colloidal activated carbon directly into polluted aquifers, allowing for *in situ* (in-place) treatment of the contamination.

CAC Converts the Subsurface Into a Purifying Filter

When applied directly into the subsurface, this patented colloidal activated carbon (CAC) material, effectively converts the subsurface into a purifying filter. Commercially available as PlumeStop® and SourceStop®, these technologies efficiently remove per- and polyfluoroalkyl substances (PFAS).

CAC Offers a Low-Cost, Zero-Waste PFAS Solution

In situ filtration using CAC is increasingly gaining widespread attention as the environmental industry seeks practical and economically viable solutions to remediate PFAS-contaminated sites. With many known benefits, including low cost and zero waste, this approach to eliminating PFAS risk provides significant advantages, including avoiding the need for permanent infrastructure, ongoing operations and maintenance, external power, and the need for PFAS waste disposal. This eBook delves into the mechanics of *in situ* PFAS remediation with CAC, explaining how this approach is used to prevent PFAS exposure risk.



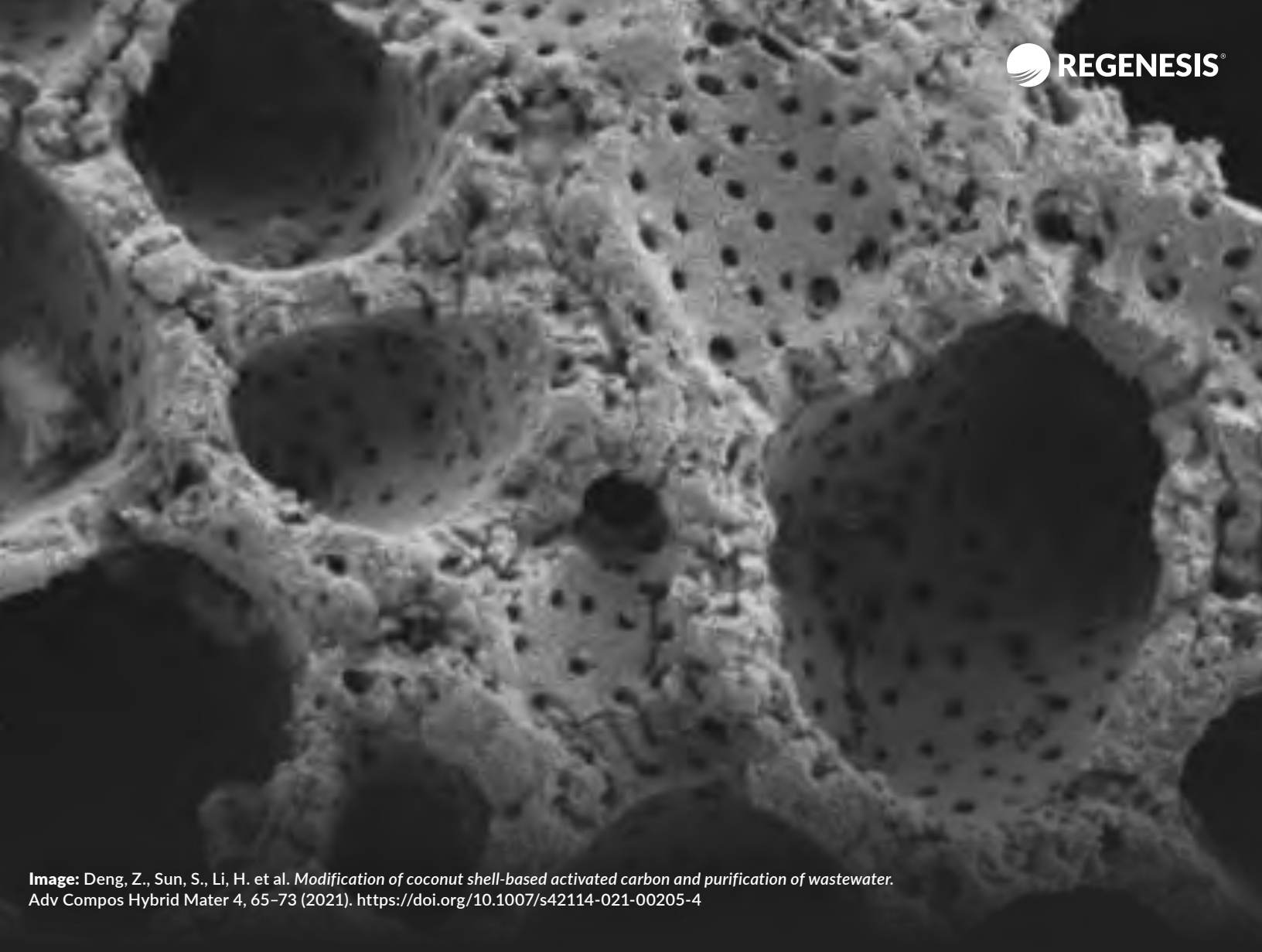


Image: Deng, Z., Sun, S., Li, H. et al. *Modification of coconut shell-based activated carbon and purification of wastewater.* *Adv Compos Hybrid Mater* 4, 65–73 (2021). <https://doi.org/10.1007/s42114-021-00205-4>

What is Activated Carbon?

Activated carbon is a highly porous form of charcoal processed to increase the surface area available for adsorption. The process converts raw natural materials, such as coconut shells into char by heating in an anoxic environment, which removes the volatile components. This char is then exposed to oxidizing gases or vapors at high temperatures—up to 1,000 degrees Celsius—resulting in a porous, honeycomb-like structure that holds contaminants.

CAC Acts Like a Giant Sponge

Many common water contaminants will stick to charcoal rather than remaining dissolved in water. Activated carbon takes the same principle to an extreme. Like a hard sponge, each carbon particle contains a network of tunnels, micropores, and nanopores. This structure results in a vast surface area, on the order of 1,000 square meters per gram, or nearly 100 acres per pound of activated carbon, making it extraordinarily effective at capturing contaminants in water.



Key Differences Between Colloidal Activated Carbon and Other Activated Carbon Material

Colloidal activated carbon, or CAC, is a specialized form of activated carbon, with particles milled to less than 2 microns in size—the size of a red blood cell—suspended in a liquid medium. This colloidal form allows the carbon particles to distribute within polluted aquifers, moving through (i.e., permeating) much larger soil pores. As the CAC material moves through the aquifer, it coats the aquifer matrix with a thin layer of activated carbon.

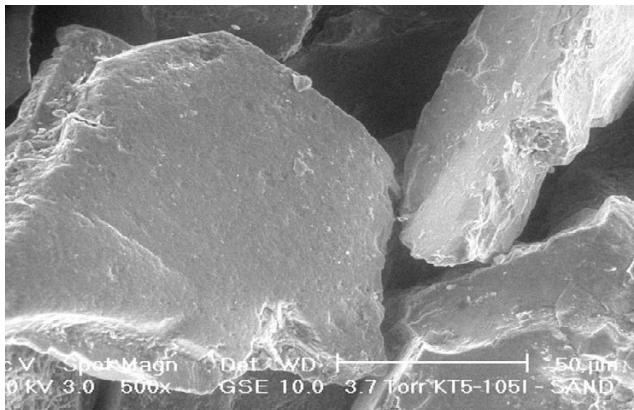
CAC is markedly different from other forms of activated carbon like powdered activated carbon (PAC) or granular activated carbon (GAC), which contain much larger activated carbon particles, typically in the range of 50 to 500 microns in size, respectively.

Their size and aggregating behavior prevent these materials from being able to be adequately distributed through the subsurface.

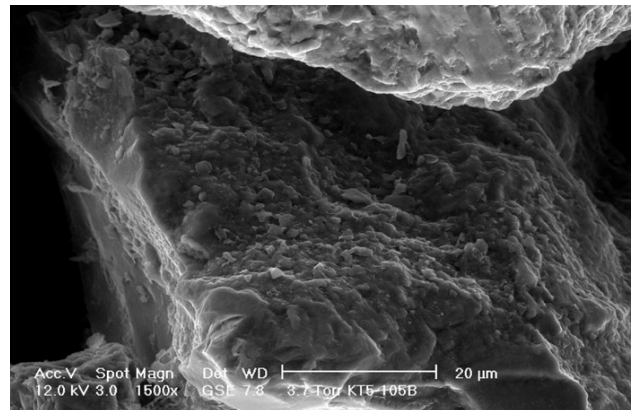
Size of Carbon Matters

The size of the carbon particles also factors into the rate of contaminant sorption as smaller particles lead to faster reactivity (Xiao, et al., 2017). CAC's tiny particle size facilitates much faster sorption kinetics than either PAC or GAC materials.

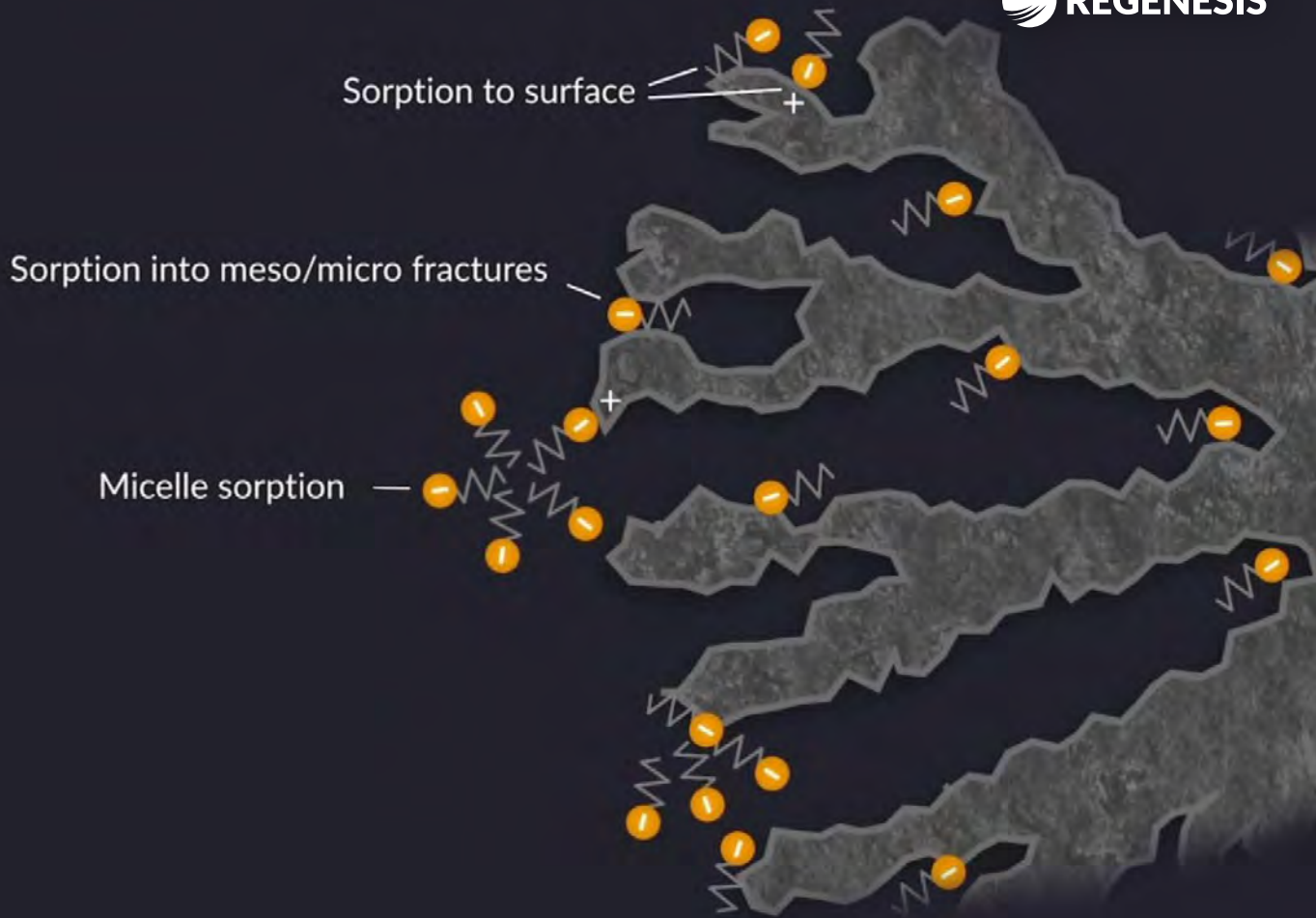
📌 On a per-pound basis, CAC's tiny particle size facilitates much faster sorption kinetics than either PAC or GAC materials.



Scanning electron microscope image of untreated sand grains (scale is 50 microns)



Scanning electron microscope image of sand grains coated with CAC (scale is 20 microns).



How Does Activated Carbon Adsorb Contaminants and What Primary Factors Govern Sorption Behavior?

Adsorption refers to the collection of molecules onto the external surface or internal surface (e.g., walls of tunnels or capillaries) of a solid. It occurs through physical and chemical forces that attract and retain contaminants onto the activated carbon surfaces. Adsorption is a dynamic equilibrium process governed by a chemical's affinity to bind to carbon and its concentration.

CAC Sorption Properties

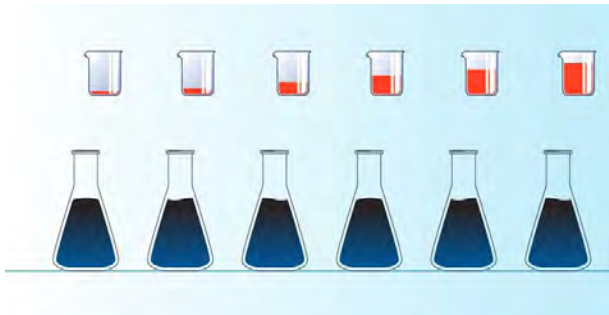
Activated carbon's affinity for organic molecules is related to the organic molecule's hydrophobicity. Those molecules with a higher relative hydrophobicity will have a greater tendency to partition out of the aqueous phase and onto the carbon surface.

Among PFAS compounds within the same class (e.g. perfluorinated sulfonic acids), PFAS molecules with structures that contain long chains of carbon atoms tend to be more hydrophobic than those with shorter chains of carbon atoms, and will therefore have a greater affinity for activated carbon. For example, PFOS (perfluorooctane sulfonic acid) having a backbone eight carbon atoms long, will sorb to activated carbon more strongly than molecular species like PFBS (perfluorobutane sulfonic acid), which only contains a four-carbon long structure.

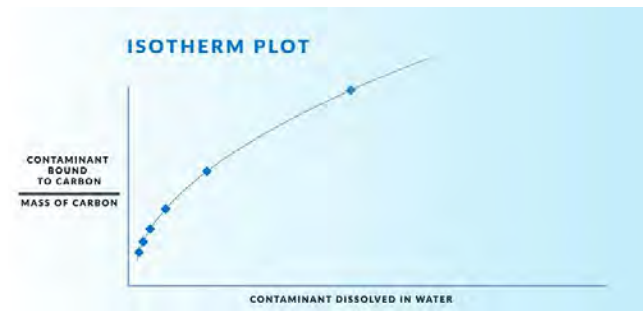
Determining Contaminant Adsorption Using Isotherms

Scientists can estimate the contaminant mass that will be bound onto a given mass of activated carbon and how much will remain dissolved in water using a type of plot known as an isotherm. Isotherms are generated in a laboratory by preparing containers of water with a prescribed amount of activated carbon and by adding an increasing amount of contaminant to each container. Following agitation, these carbon-water-contaminant mixtures are given time to reach equilibrium while maintaining a constant and equal temperature for all.

Once equilibrated, carbon and water samples from each system are analyzed for contaminant concentration and plotted on a graph. The y-axis represents the mass of contaminant bound to the activated carbon per mass of carbon while the x-axis represents the mass of contaminant dissolved in water. The data are graphed, and a mathematical curve fit is derived to create the isotherm plot. This isotherm can then be used to predict the relative concentration of a contaminant that will adsorb to carbon versus what will remain in water in a given system.



Increasing amounts of a contaminant are added to a series of beakers with the same mass of carbon and volume of water.



Depiction of an isotherm plot

The Freundlich Isotherm

The Freundlich isotherm, named for Herbert Freundlich, is the most representative empirical isotherm model for estimating adsorption of contaminants onto activated carbon.

The Freundlich Isotherm equation is expressed as:

$$q_e = K_f C_e^{1/n}$$

Where:

- q_e - represents the mass adsorbed per unit mass of adsorbent (adsorption capacity)
- K_f - is a constant related to the adsorption capacity, known as the Freundlich coefficient
- C_e - represents the equilibrium concentration of the adsorbate in solution
- n - is a constant associated with adsorption intensity, known as the Freundlich constant.

In referring to the isotherm plot, when a low concentration of a contaminant is in the presence of a high amount of activated carbon, the data point will plot on the left side of the isotherm. This means that most of the contaminant is bound to the carbon, with little remaining in the water. As more and more contaminant is added to the system with a fixed amount of carbon, a higher concentration remains in the water and the data will be plotted farther to the right. At some point, the carbon will reach its adsorption capacity and any further contaminant added will remain in the water.

REGENESIS works with some of the world's leading groundwater academic researchers in developing isotherms for various contaminants, including PFAS.

How Does Colloidal Activated Carbon Remediate PFAS?

PlumeStop and SourceStop CAC materials are applied directly into the subsurface, which permanently coats the aquifer pore structure with an activated carbon layer. As groundwater migrates through a CAC treatment zone, the contaminants become rapidly adsorbed onto the activated carbon particles coating the aquifer matrix and they are removed from the dissolved phase.

Once Injected, CAC Immediately Reduces PFAS Levels

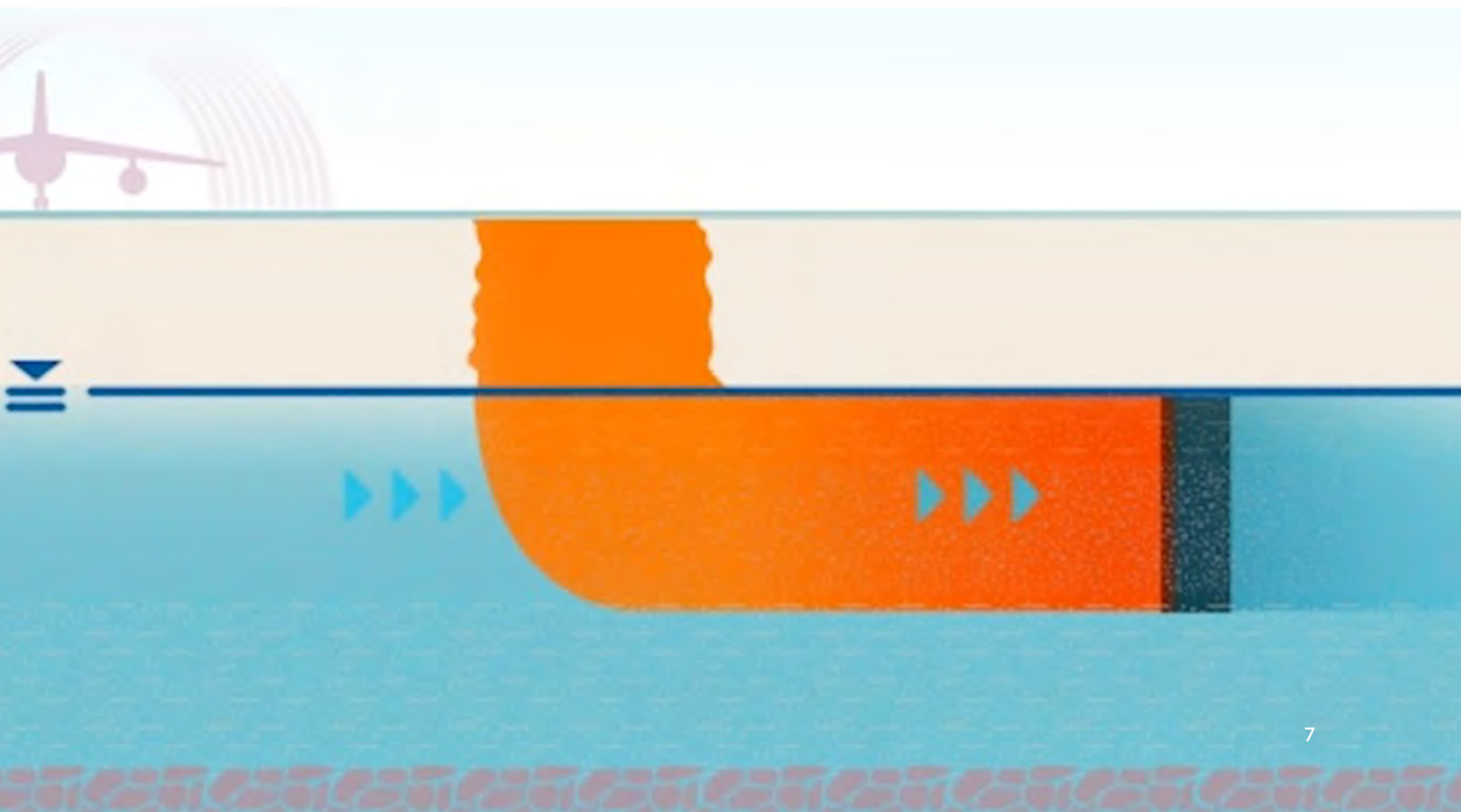
The effects of the injected CAC media are immediate. Typically, PFAS levels are quickly reduced below regulatory standards within days of application. These reductions are sustained over the long term. Other contaminants that might be co-present, including jet fuel contaminants remaining from past firefighting activities, are also effectively removed.

In a firefighting training area at an airport where historical aqueous film-forming foam (AFFF) discharges contaminated the soil and groundwater

with PFAS, CAC can be injected downstream of the discharge area. This creates a below-ground activated carbon filter that immediately begins removing these contaminants from the groundwater.

CAC Offers Faster Adsorption and Higher Residence Time

Compared to pumping the contaminated groundwater above ground and filtering it through tanks or beds of activated carbon, filtering PFAS *in situ* removes contaminants with much greater efficiency. This efficiency results from the exceptionally high surface area of the aquifer pore structure coated with activated carbon. The small size of the carbon particles offers much faster adsorption of the contaminants and a much higher residence time (i.e., contact time) for contaminant adsorption to occur. Compared to the fast velocities of pumped groundwater and limited surface areas for filtration in pump-and-treat systems, groundwater moves much more slowly and across a much greater surface area in a CAC-filtration zone.

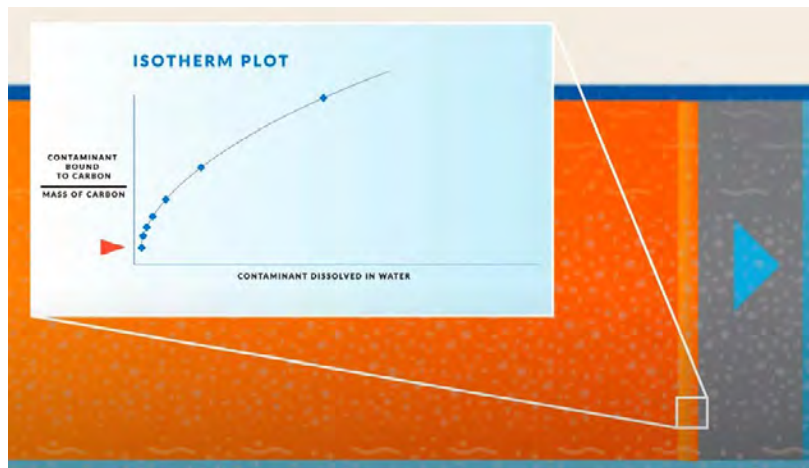


How Does a CAC Barrier Contain PFAS Over the Long Term?

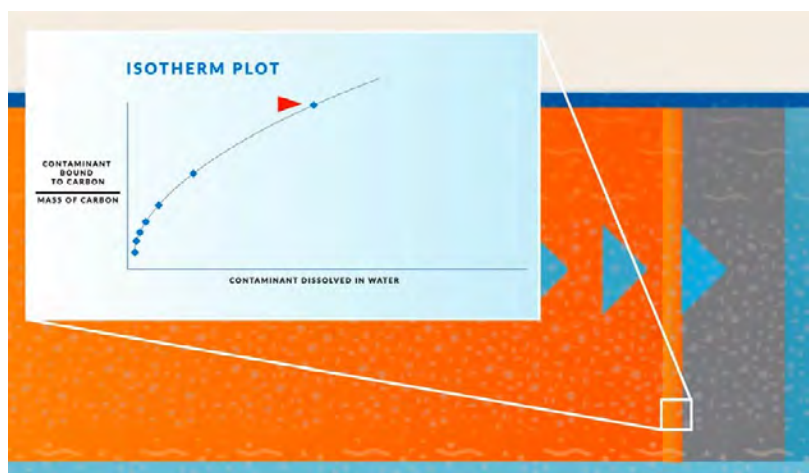
Contaminants entering the first few centimeters of a fresh colloidal carbon treatment zone in an aquifer are rapidly stripped out of solution as they begin to adsorb onto the relatively high available mass of activated carbon. When considering the isotherm plot, this equates to a point at the bottom left (see illustration in upper panel below).

Over time, as more and more contamination accumulates on the micron-scale activated carbon, more contaminant begins to remain in the solution, plotting further to the upper-right on the isotherm (lower panel below). As the contaminated groundwater slowly moves downgradient, rollover begins to occur. Rollover is when the dissolved contaminants move forward onto the fresh activated carbon surface in the next few centimeters of a CAC-treated aquifer, where they again become tightly adsorbed.

High available CAC surface area is initially present on the influent side of the barrier, with a representative data point on the isotherm shown at the bottom-left.



The number of available sorption sites on the CAC becomes lower on the influent side of the barrier over time (corresponding to data point in upper right of isotherm plot). Eventually, capacity is reached and contaminant rollover onto the next few centimeters of barrier begins, restarting the process.





How Does Breakthrough Occur and How is it Mitigated?

If the influx of PFAS to the colloidal carbon treatment zone remains unabated, contaminants will eventually roll over enough to break through the treatment zone. However, due to the efficiency of *in situ* colloidal carbon treatment to adsorb PFAS and the relatively low velocity of groundwater movement, the breakthrough of unabated PFAS plumes is not expected to occur for many decades in most cases. Industry-recognized modeling experts have shown that a single application may be effective for more than 60 years (Carey et al., 2022, Carey et al., 2024).

Flexible Design Choices Mitigate Breakthrough

These below-ground CAC filters are engineered to retard PFAS migration based on site-specific mass-flux demands and treatment goals. PFAS contaminants migrating into a PlumeStop barrier are slowed by orders of magnitude, effectively halting their movement for decades. For example, Carey et al. (2024) showed through modeling that PFOA

migration would be slowed from 20 feet per year to approximately 0.2 ft per year in a hypothetical PlumeStop barrier placed at the leading edge of a large PFAS plume at a US military facility. The modeled 15-foot-wide barrier transecting the plume would stop PFAS migration for 66 years. This timeframe could be further extended by increasing the treatment zone dimension along the flow path, the CAC concentration applied, or in combination.

In the event of a contaminant breakthrough, CAC can be easily re-applied to restart the remediation clock over again. Any reapplication will likely be much more limited than the original treatment, and will only need to target more prominent contaminant mass-flux zones.

📌 “In the event of a contaminant breakthrough, CAC can be easily re-applied to restart the remediation clock over again.”

Can CAC *In Situ* Filtration Eliminate PFAS Exposure Risk Permanently?

When the upgradient source of PFAS is remediated, the flux of PFAS contaminants entering a CAC-treated zone is reduced, slowing the rate of PFAS rollover. At many sites where remediation of the source is accomplished, the contaminant flux may be reduced to a degree where residual PFAS migrating into a CAC treatment zone will not move out of it at concentrations above regulatory levels. This process is analogous to the 'peak shaving' strategy used by civil engineers for stormwater control (Newell, et al., 2022).

Therefore, when remediation of a PFAS source area is coupled with *in situ* CAC filtration treatment in the plume, a permanent solution to prevent exposure risk becomes feasible at many sites.

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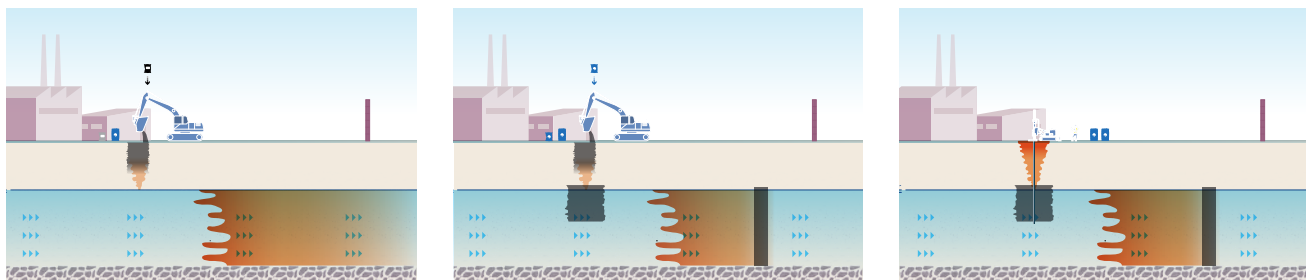


PFAS Source Area Remediation Using SourceStop

To date, the remediation of PFAS source areas has mostly involved physical removal (i.e., excavation and disposal) or the direct mixing of common materials like GAC to promote PFAS sorption and reduce leaching potential.

SourceStop, a concentrated CAC, was developed to improve source area treatment effectiveness and longevity. Available in solid and liquid forms, SourceStop can be applied to the vadose soils, capillary fringe or groundwater at PFAS source areas.

SourceStop Solid reduces the leachability of the soil PFAS contamination and prevents further discharge into the groundwater. SourceStop Liquid is injected into the capillary fringe and groundwater under the spill location, reducing the mass flux of PFAS migrating from the source area.



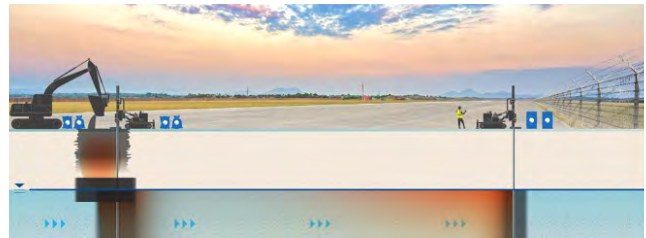
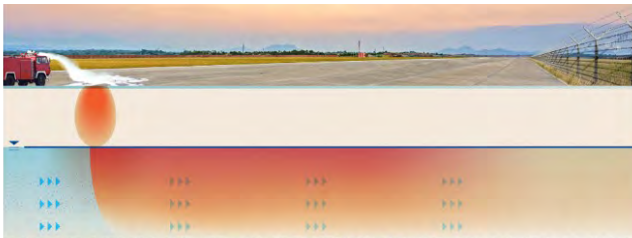
SourceStop is available in solid and liquid forms, and can be applied to the vadose soils, capillary fringe or groundwater at PFAS source zones.

Full-Spectrum PFAS Soil and Groundwater Treatment

Away from the source area, the dissolved phase contaminant plume can be intercepted by installing a permeable sorptive barrier (i.e., *in situ* CAC filter) to protect downgradient receptors. This treatment can be warranted to provide certainty to the site owners and regulators.

By combining SourceStop treatments at the source area and plume treatments using PlumeStop CAC

permeable sorptive barriers, the contaminant discharge into the groundwater is minimized and the residual plume entering the down-gradient barrier is weakened substantially. This enables the PlumeStop CAC barrier to continue operating with potentially no re-injection required. The result is a long-term solution with minimal cost, no ongoing energy or carbon emissions, and no waste generated.



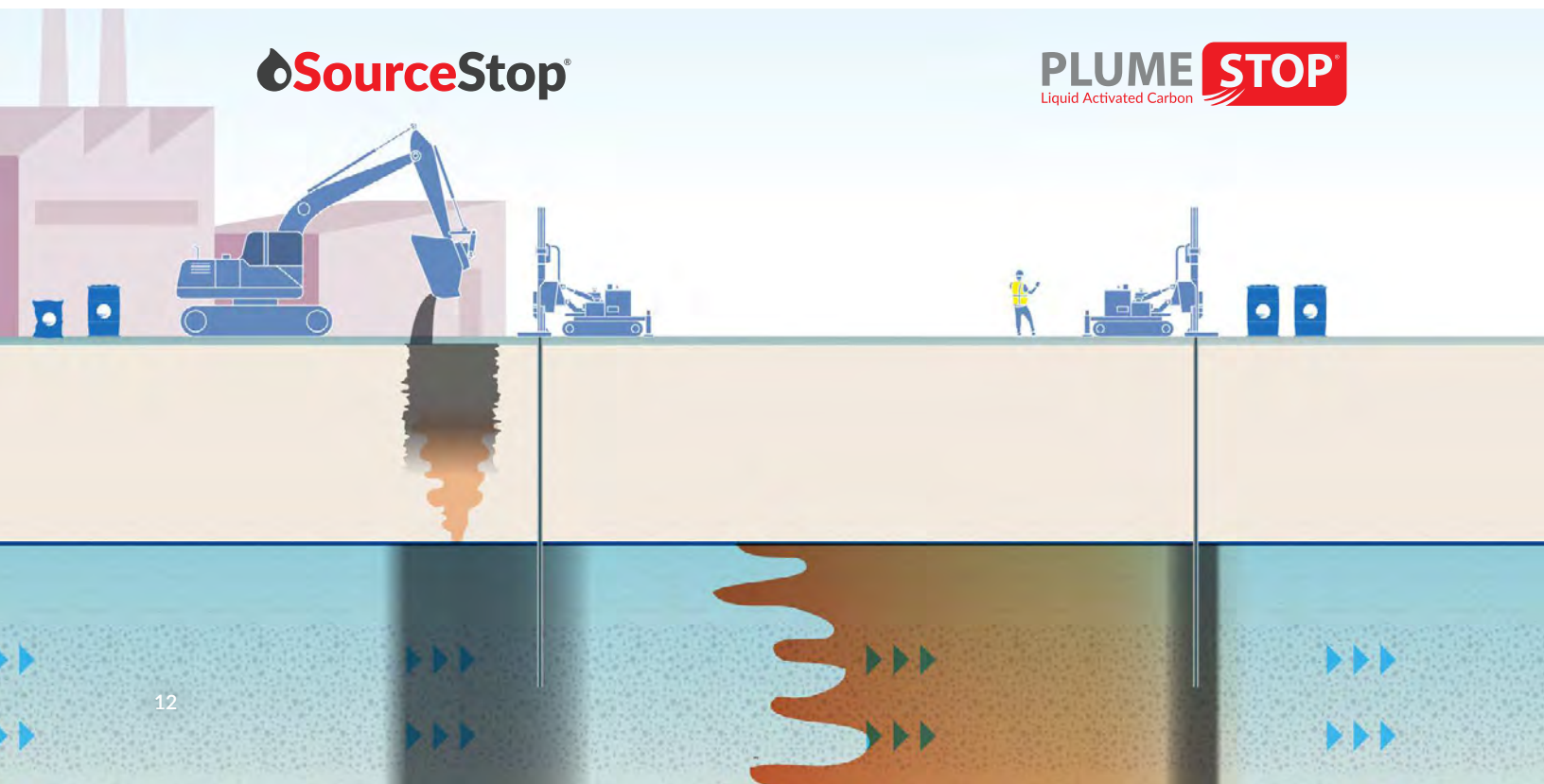
In the left image, AFFF containing PFAS is sprayed on an airport runway, causing a PFAS plume to develop in groundwater. In the right image, colloidal activated carbon is applied into the subsurface beneath the release source (SourceStop) and in a downgradient permeable sorptive barrier (PlumeStop) to reduce PFAS to non-detectable concentrations in groundwater and effectively eliminate PFAS risk caused by the AFFF release.



Scan or Click

PFAS Effectively Treated at Over 55 Sites

Since the first successful application of PlumeStop to address PFAS over 7 years ago, REGENESIS continues to lead the industry in the number of PFAS sites treated globally. With over 55 sites treated to date worldwide, the use of PlumeStop and SourceStop is the preferred choice for fast, cost-effective, and field-proven performance to eliminate PFAS risk in soil and groundwater.



SourceStop®

PLUME STOP®
Liquid Activated Carbon



Conclusion

Using PlumeStop and SourceStop CAC materials to filter PFAS out of groundwater *in situ* presents a low-cost, zero-waste, and easy-to-implement approach that can be effectively deployed at most PFAS-contaminated sites.

The *in situ* CAC remediation approach is founded on long-established empirical testing methods to create isotherms, which enable scientists and engineers to quantify contaminant adsorption onto activated carbon. Accordingly, the amount of CAC needed to remediate PFAS can be estimated based on the rate of contaminant migration (i.e., mass flux) into a CAC-treated zone.

Once PFAS or other contaminants migrate into a CAC filtration zone, their rate of movement is retarded by

magnitudes, typically resulting in many decades of effectiveness following a single treatment. Where the mass flux is well defined, *in situ* PFAS remediation solutions can be accurately designed to meet site-specific risk-reduction goals.

By strategically applying CAC at both the source and downgradient areas of a plume, it is possible in many cases to permanently eliminate PFAS exposure risk, offering a one-and-done, immediately effective and low-cost PFAS treatment solution.

- ✔ Using PlumeStop and SourceStop CAC materials to filter PFAS out of groundwater *in situ* presents a low-cost, zero-waste, and easy-to-implement approach that can be effectively deployed at most PFAS-contaminated sites.



References



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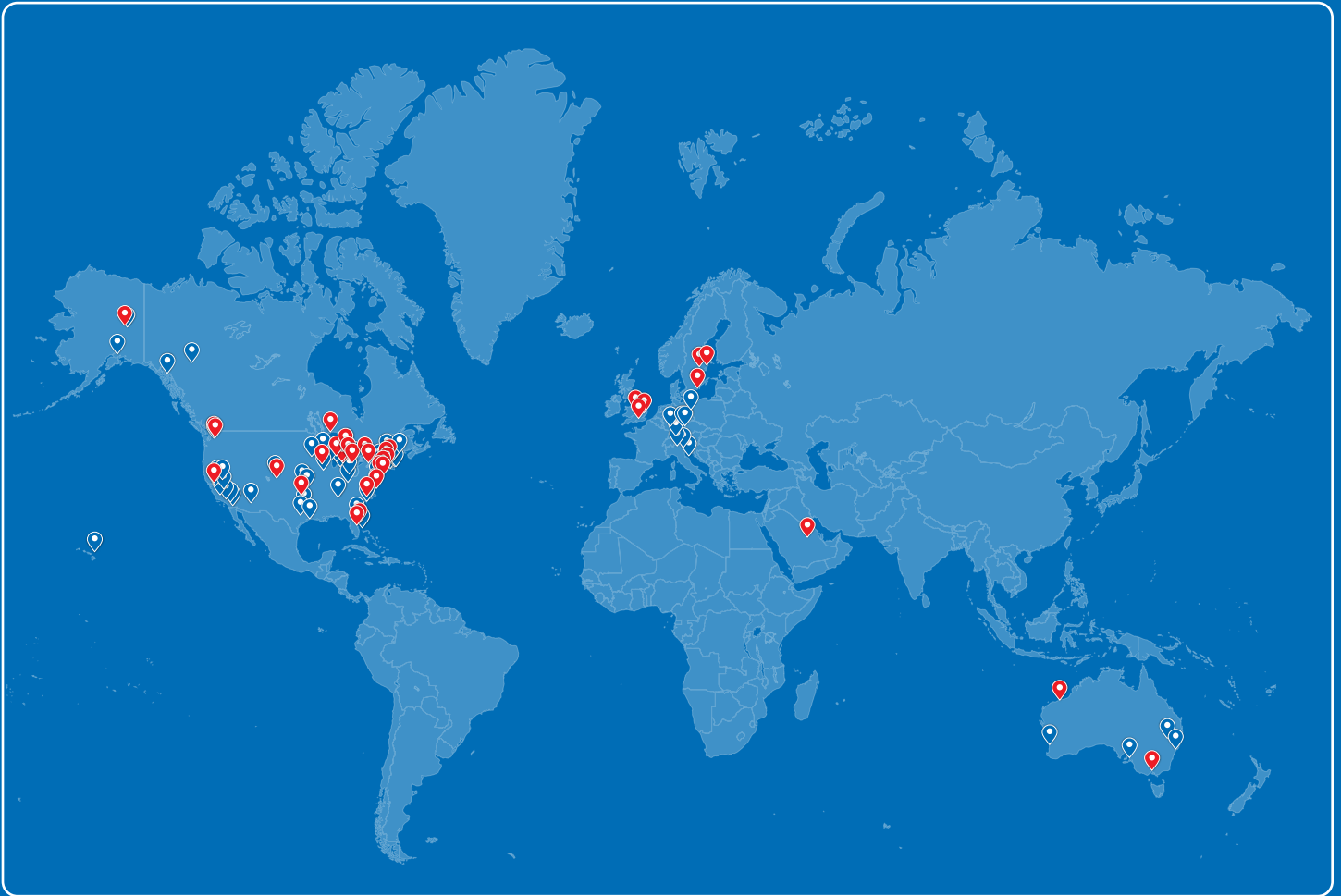


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We're Ready to Help You Find the Right Solution for Your Site



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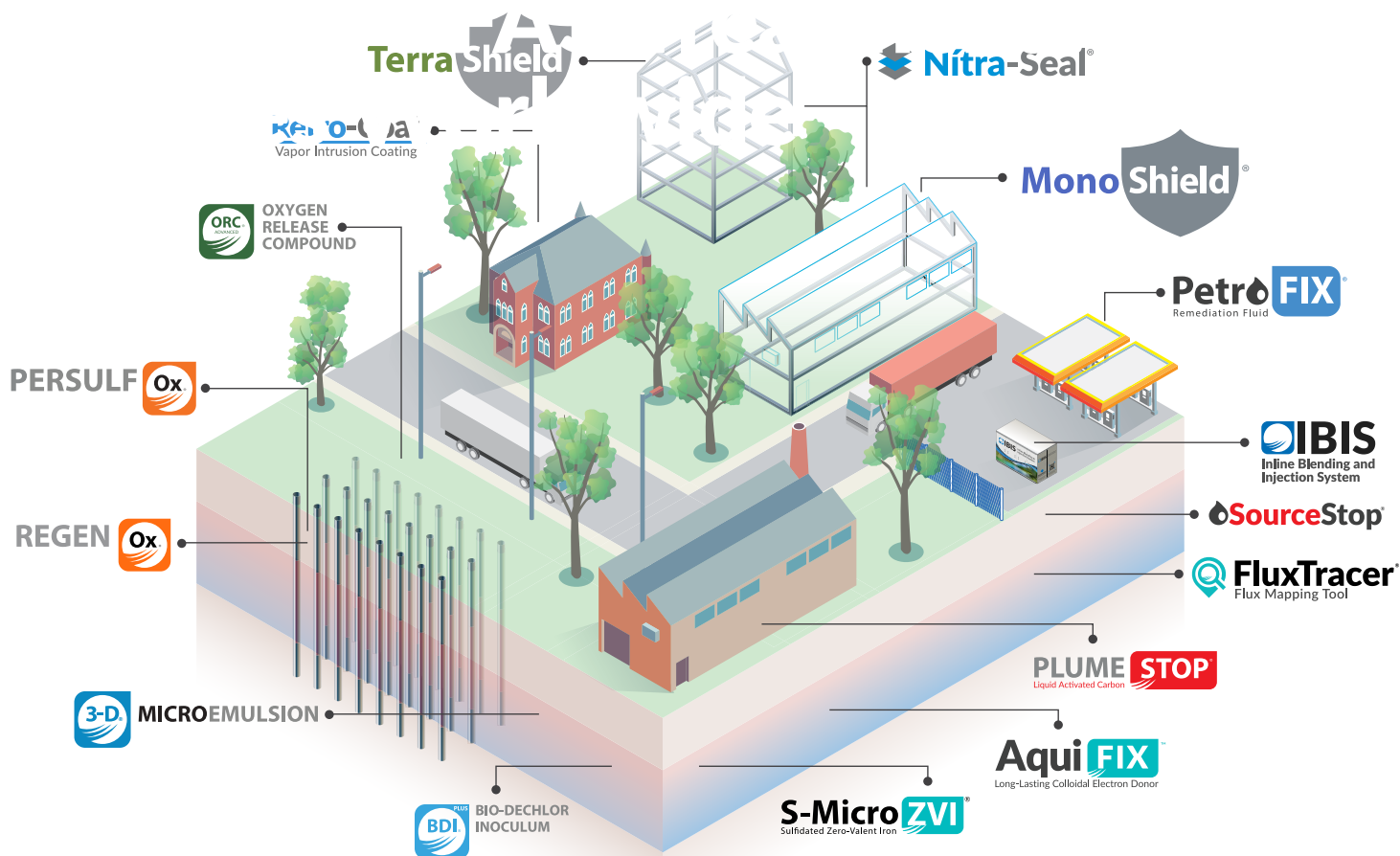
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About REGENESIS

At REGENESIS we value innovation, technology, expertise and people which together form the unique framework we operate in as an organization. We see innovation and technology as inseparably linked with one being born out of the other.

Inherently, innovation imparts new and better ways of thinking and doing. For us, this means delivering expert environmental solutions in the form of the most advanced and effective technologies and services available today.

We value expertise, both our customers' and our own. We find that when our experienced staff collaborates directly with customers on complex problems, there is a high potential for success including savings in time, resources and cost.

At REGENESIS we are driven by a strong sense of responsibility to the people charged with managing the complex environmental problems we encounter and to the people involved in developing and implementing our technology-based solutions. We are committed to investing in lasting relationships by taking time to understand the people we work with and their circumstances. We believe this is a key factor in achieving successful project outcomes.

We believe that by acting under this set of values, we can work with our customers to achieve a cleaner, healthier, and more prosperous world.