Remediating Petroleum Contaminants with Activated Carbon Injectates

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"Any sufficiently advanced technology is indistinguishable from magic." - Arthur C. Clarke

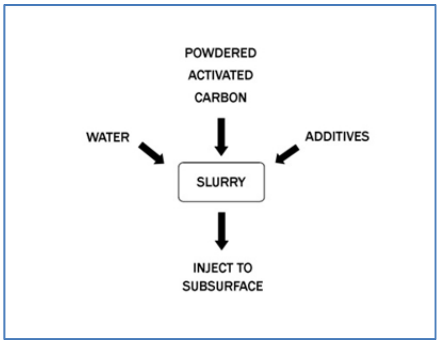
1. INTRODUCTION

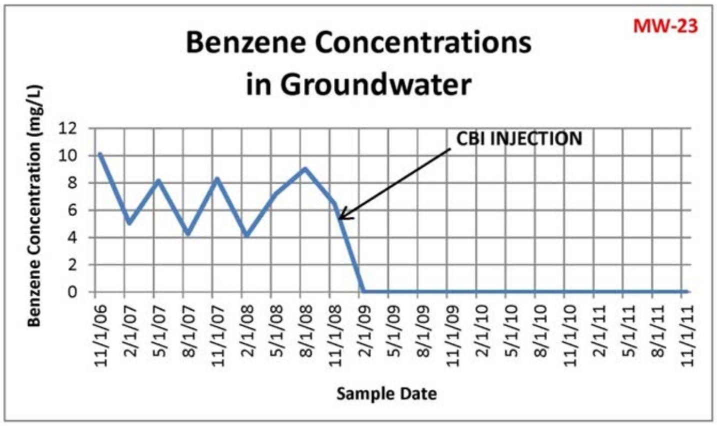
Injecting an activated carbon-based slurry into the subsurface to remediate petroleum contaminated soil and groundwater is proving to be fast, economical and effective. But even though this worthwhile technology has been available since 2002, it's used in only a few states.

In this paper, I share the results of my own recent research on the use of "carbon-based injectates" (CBI). My inquiry includes a survey of regulators across the U.S. to determine how widespread the use of CBI is and to learn what results CBI users have observed. I also discuss concepts related to injection design, equipment requirements, and product placement. I hope that as a result of this study readers will learn more about CBI as it relates to their own projects and as a framework for future research in this rapidly evolving field.

2. WHAT IS AN ACTIVATED CARBON-BASED INJECTATE?

In this paper, I define activated carbon-based injectate (CBI) as slurry, comprised primarily of powdered or pulverized activated carbon, mixed with water and possibly other additives and injected into the subsurface to remediate subsurface soil and groundwater impacted by petroleum hydrocarbons. Carbon-based injectates are also used to remediate chlorinated solvents and other chemicals-of-concern (COCs). While much of the information presented here can be applied to other types of injectates and other target COCs, my primary focus is CBI to remediate petroleum hydrocarbons.





My firm began injecting CBI in Colorado in early 2006 to remediate petroleum contaminated sites, primarily related to leaking underground storage tanks. We had success early on using this technology but found many of the consultants and regulators we worked with were reluctant to use CBI. This may have been partly due to doubts about injection technology due to failures of other injectates. As our own understanding of the steps to properly design and inject CBI evolved, we began seeing unparalleled results in sites remediated with CBI. In fact, the success rates were so great that we began questioning how rates like these were even possible. If we were having so much success, we thought, wouldn't others in the industry see the same results? And it wasn't just on our sites. One consulting company for whom we routinely inject CBI was so impressed with the results that they told us they were worried about their job security!

3. HOW WIDESPREAD IS THE USE OF CARBON-BASED INJECTATES?

As we began to question the incredible results we were seeing using CBI to remediate petroleum contaminated sites, and considering the significant investments we were making in injection equipment and our own mixing and dust control technology, I began to query regulators in other states to determine:

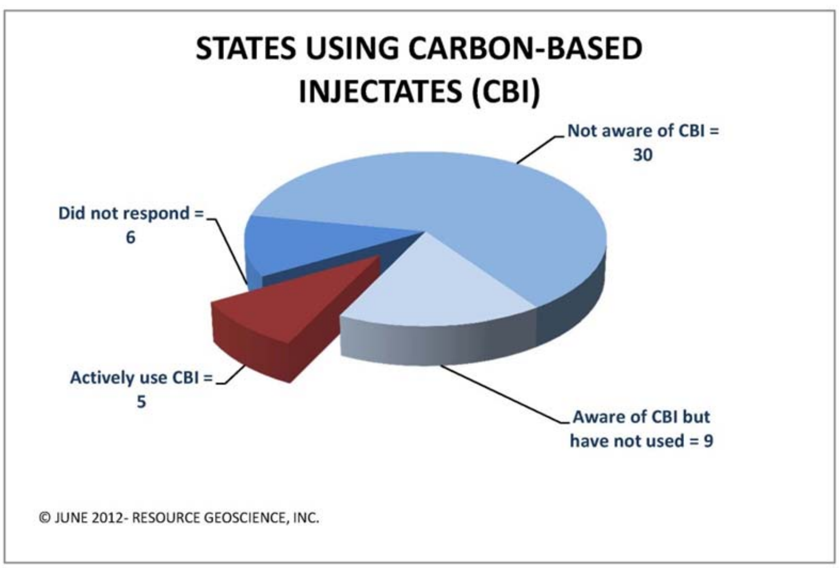
1. Have they heard of CBI?
2. If they're using CBI, what results are they seeing?

I sent a brief email survey to regulators overseeing leaking petroleum underground storage tank programs in all 49 states outside Colorado along with the Environmental Protection Agency (EPA), Air Force Center for Engineering and the Environment (AFCEE), Department of Energy (DOE) and Department of Navy Environmental Program (DNEP).

While the results are not necessarily statistically valid, they're interesting in a broad sense. As noted on the chart below, only five (5) respondents indicated they actively use CBI for remediation of petroleum contaminated soil and groundwater. An additional nine (9) had heard of CBI but were not aware of any projects in their state where CBI was used.

Based on my survey, the states actively using CBI for remediation of petroleum hydrocarbons include Colorado, Wyoming, Kentucky, Oregon and Utah. The results of my survey should be used with caution, however. It is entirely possible that CBI may be used in a particular state but the regulator I contacted was simply not aware of its use. Some of the states that did not respond may also use CBI. Understandably, people are often reluctant to respond to this kind of survey. For example, one regulator responded: "Is this some marketing ploy?"

The respondent from the EPA Technological Innovation and Field Services Division (EPA-TIFSD) indicated personnel surveyed in their office and in EPA's Office of Research and Development (EPA-ORD) did not have much knowledge of CBI. This is important since these offices generally are clearinghouses for technologies used in the remediation of contaminated sites.



In general, it appears using CBI to remediate petroleum contaminated soil and groundwater is not widespread. Based on the success rates we've seen in Colorado on our own projects and on projects where we've injected for other consultants, it's curious why the use of CBI is not more widespread. Especially when I hear responses from regulators in different states that have experience with CBI saying such things as:

"…showed miraculous results…"
"…used…at approximately 14 UST sites with 100% effectiveness thus far..."
"…shows promise as an effective remedial strategy."

4. POSSIBLE REASONS FOR THE APPARENT LIMITED USE OF CARBON-BASED INJECTATES

Most of us who've practiced in the environmental remediation field for any length of time have seen numerous technologies fail, sometimes dramatically. Some technologies, even when showing only limited success, continue to be used for long periods as no apparent cost-effective alternatives exist. Pump and treat is an example of a technology that continued to be used for many years at considerable expense even though the results were less than satisfactory for most sites. While various injectates have been around for at least the last several decades, their success rates have been mixed.

It seems that at every trade show someone is presenting the latest, greatest injectate or technology guaranteed to remediate sites. In all fairness, there are some great products available that often fail due to problems in the data acquisition and design phase or, more commonly, in the delivery (injection) phase. Some injectates on the market, however, are nothing more than "snake oils." A failure of an "injectate" at a particular site may translate to a perception in a failure of <u>all</u> injectates. These failures, whether due to faulty designs, injection technique, or just bad products, have tarnished the reputation of injectates in general.

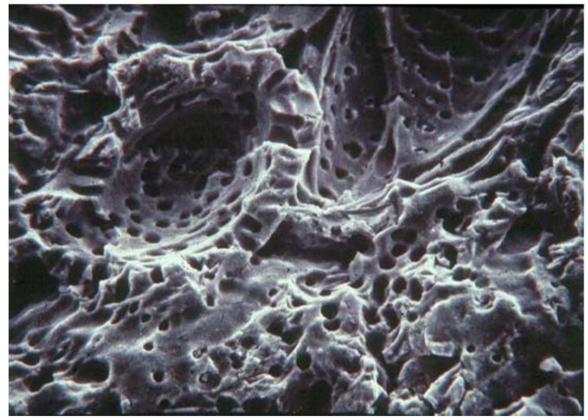
Over the years, we've become comfortable with other proven technologies such as soil vapor extraction, air sparging and dual-phase extraction among others. Dig-and-haul is still used frequently for many small, and sometimes large, remediation projects. While all these technologies have their flaws, in general, they work – sometimes quickly (dig and haul) and sometimes slowly. But, given enough time, they work. Most mechanical systems also are forgiving; if it doesn't work this year, leave it running for another year or so and it probably will.

But injectates are different. We expect them to work quickly and yet we can't easily see or monitor closely what's happening in the subsurface. Did we achieve good placement of the injectates? What will happen if we need to come back and do another round of injections? Will we see rebound? Which product should we use and who has the experience and track record to ensure it's injected properly?

5. AVAILABLE PRODUCTS

My research suggests a limited number of carbon-based injectates are available. A recent report by the Norwegian Research Council (NGI) summarizes a pilot study in Norway where activated carbon alone was used as an amendment to remediate hydrophopic organic contaminants (HOCs) in marine sediments[1]. The NGI report also references two pilot studies using activated carbon, one in California and one in New York. Enviro-Equipment, Inc. distributes a product called GR-320-IRC™ which is a pulverized activated carbon with a select gradation which makes their product amenable to slurry injection but does not include proprietary additives[2]. We inject a patented product called BOS-200® sold by Remediation Products, Inc. (RPI). The only other CBI I encountered was a product called Liquefied Activated Carbon sold by SHAC Environmental Products, Inc. which appears to be used primarily for sewage treatment. While other CBI products might be used elsewhere, these are the only products I found during my research.

6. CARBON-BASED INJECTATE THEORY



Microscopic view of activated carbon showing porous structure. (Used with permission: General Carbon Corp.[3])

Activated carbon (AC) has long been used to remove organic impurities from liquids and air. Generally, in the environmental field, we store AC inside vessels and then pump groundwater or air, contaminated with volatile organics, through the carbon vessel. This process is similar to using a carbon filter on a household sink to remove impurities from tap water. In the case of carbon-based injectates, we turn this process on its head and instead inject AC into the contaminant mass itself and remediate the contaminants in-situ.

AC is extremely porous and provides a huge surface area; one pound of AC can provide a surface area of over 5 million square feet. AC has an affinity for organic chemicals, such as petroleum hydrocarbons, and organic chemicals will physically bond (adsorb) to the micropores of the AC through Van der Waals forces. This process is analogous to iron particles attracted to a magnet. Once the chemicals are adsorbed to the carbon's surface, the process generally can be reversed only by heating the carbon to a very high temperature, by use of a solvent, or through microbial processes. AC has been found to remain stable under extreme environmental conditions for long periods of time. This is one reason spent carbon is allowed to be disposed in landfills; the chemicals remain physically bonded to the carbon and will not leach. When Toxicity Characteristic Leaching Procedure (TCLP) analyses, designed to determine the mobility of contaminants in a landfill environment, are performed on spent carbon, the contaminants are found to be immobilized in the carbon and are not available to leach into the landfill.

Carbon-based injections take advantage of this process by placing the activated carbon in contact with the target petroleum hydrocarbon contaminants in the subsurface. The contaminants adsorb to the carbon, essentially sequestering the contaminants onto the carbon surface. This sequestration is analogous to solidification and stabilization, often using cement, which reduces the mobility of contaminants and has been approved by many regulating agencies as an alternative to removing contaminants. Sequestering by itself doesn't eliminate contaminants; it prevents them from migrating.

Even with its huge surface area, AC can only adsorb a limited amount of hydrocarbons. Once that limit is reached, no additional hydrocarbons will be adsorbed to the carbon. In the treatment of liquids or gasses, when no additional contaminants can adsorb to the carbon, the carbon is referred to as "spent." Once AC is spent, it must be either reactivated or disposed and replaced.

7. HOW MUCH WILL CARBON-BASED INJECTATES ADSORB?

If CBI is injected into the ground but subsequently becomes spent, contaminants will migrate past the CBI and efforts to remediate the site become ineffective. Once the carbon is spent, one of three things must occur:

1. Remediation stops; all remaining contaminants will continue to be available to mobilize,
2. Additional CBI must be injected,
3. The CBI already injected must be recharged.

Thus, it is important to evaluate the volume of contaminants expected to be adsorbed by a given amount of CBI.

7.1 Dissolved-phase adsorption

Activated carbon will generally adsorb from 1 to 35 weight percent.[4] This means that 100 pounds of carbon will adsorb between 1 pound and 35 pounds of contaminants before the carbon is spent. If we consider a single injection point[5], assume a 5 ft. Radius of Influence (ROI) from our injection point and use 2 ft. injection intervals (the spacing vertically between injections), the volume of liquid present in the interconnected pore spaces will be approximately:

Soil Type	Effective Porosity (Φe)	Volume of Liquids (gals)
Gravel	0.24	282
Sand	0.33	388
Silt	0.20	235
Clay	0.06	70

If we assume the following:

- A conservative (elevated) dissolved Total Petroleum Hydrocarbon (TPH) concentration in groundwater of 200 mg/L,
- A worst case adsorption rate of 1 weight percent,
- A CBI injection loading of 2 lb. per gallon of injectate,
- A CBI injection volume of 40 gallons at this 2 ft. interval = 80 lbs CBI,
- Each CBI injection interval then will theoretically adsorb 0.8 lbs. of contaminants[6].

We then can calculate the potential for the CBI to adsorb all the dissolved contaminants:

Soil Type	Volume of Liquids (gals)	Total TPH (lbs)
Gravel	282	0.47
Sand	388	0.65
Silt	235	0.39
Clay	70	0.12

We can see that, assuming proper distribution of the CBI, 80 pounds of CBI (enough to adsorb 0.8 lbs of contaminants) might easily adsorb the amount of hydrocarbons dissolved in the groundwater.

7.2 Soil contaminant adsorption

The ability for typical CBI loadings to completely adsorb all the contaminants in soil isn't quite as forgiving. If we assume:

- A TPH concentration in soil of 500 mg/kg,
- A worst case adsorption rate of 1 weight percent,
- A need to adsorb <u>all</u> contaminants found in soil (which is unreasonable since soil alone will adsorb and immobilize at least some amount of hydrocarbons),

- A CBI injection loading of 2 lb. per gallon of injectate,
- A CBI injection volume of 40 gallons at this 2 ft. interval = 80 lbs CBI,
- As before, each CBI injection interval then will theoretically adsorb 0.8 lbs. of contaminants.

We then can calculate the potential for the CBI to adsorb all the contaminants present in the soil:

Soil Type	Assumed In-Place Dry Density (lb/ft^3)	Total TPH (lbs)
Gravel	100	7.9
Sand	95	7.5
Silt	80	6.3
Clay	75	5.9

If we inject only enough CBI to adsorb 0.8 lbs of contaminants our project might be unsuccessful. If we assume, however, a slightly higher adsorption rate, assume some of the contaminants are adsorbed to the soil mass, or increase our CBI loading or volume, it's possible the CBI will perform satisfactorily.

7.3 Non-aqueous phase liquid adsorption

So far, we've focused on dissolved-phase contaminants and soil contaminants. Even if we do a great job remediating dissolved-phase and soil contaminants, our efforts will generally be wasted if we don't properly identify and remediate any potentially migrating non-aqueous phase liquids (NAPLs). These free-phase contaminants in all cases are the "source" of contamination in the subsurface, resulting in dissolved-phase, sorbed soil and vapor phase contaminants.

If we rely entirely on the adsorptive capacity of AC to remediate NAPLs, we see that it may be impractical to inject enough CBI to fully adsorb free-phase liquids. Assuming:

- A LNAPL specific gravity of 0.7,
- A best case adsorption rate of 35 weight percent,
- A CBI injection loading of 3 lb. per gallon of injectate (generally the upper practical limit),
- A CBI injection volume of 40 gallons at this 2 ft. interval = 120 lbs CBI,
- In this case, each CBI injection interval will then theoretically adsorb 42 lbs. of contaminants.

Soil Type	Total Volume of LNAPL (gals)	Total Pounds of LANPL
Gravel	282	1,647
Sand	388	2,267
Silt	235	1,373
Clay	70	409

Even using conservative (best-case) assumptions, remediating NAPL using the adsorptive capacity of the AC itself may be impractical.

These calculations suggest AC alone may not have sufficient capacity to physically adsorb enough contaminants to meet our goals, except at those sites with minimal contaminant concentrations.

7.4 In-situ regeneration of carbon-based injectates

It appears likely that some type of in-situ regeneration of the CBI is occurring at sites with elevated contamination; otherwise we would see reductions in contaminant concentrations but not the elimination of contaminants. As we saw earlier, activated carbon can be regenerated by heating the carbon to an elevated temperature, using an organic solvent, or through microbial processes. Since we can't regenerate CBI already injected into the subsurface by heat or an organic solvent, we must rely on microbial processes.

Studies have long shown that indigenous microorganisms exist wherever hydrocarbon contaminants are found. This is one reason air-sparge and soil vapor extraction systems are effective. While part of the reduction in contaminants is due to aromatics volatizing, the bulk of remediation is thought due to an increase in the dissolved oxygen in groundwater and oxygen in soil, stimulating the indigenous microbes which subsequently degrade the petroleum hydrocarbons.

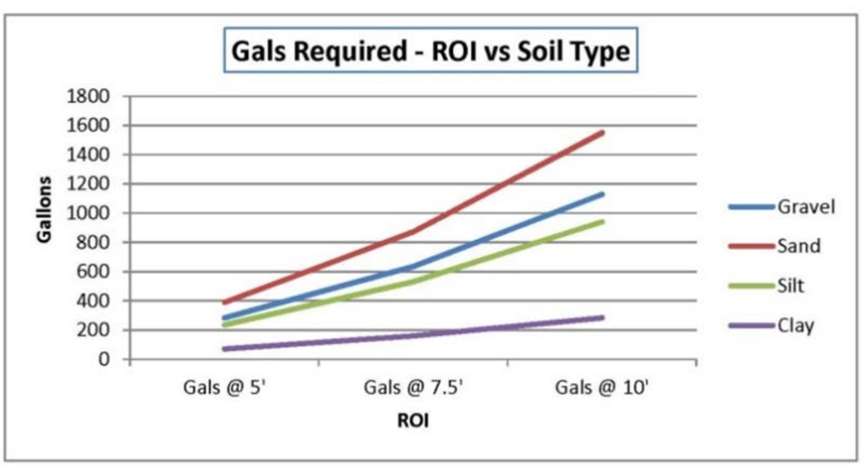
While in some cases it might be possible to inject enough CBI to rely entirely on sequestration of the contaminants, it's likely the AC in the CBI will need to be regenerated if it's expected to accept all the contaminants typically found at most release sites. It's possible that indigenous microorganisms could provide this regeneration. Enviro-Equipment, Inc.'s GR-320-IRC™ injectate relies on indigenous microorganisms for regeneration.

Researchers continue to study the advantages and disadvantages of indigenous microbes versus cultured, exogenous organisms and how they interact in aerobic and anaerobic environments. One concern is that indigenous microbes might not perform satisfactorily with CBI due to the pH and oxygen swings occurring in the subsurface environment after CBI injection. Remediation Products, Inc.'s BOS-200® combines activated carbon, a sulfate reduction media, micronutrients and facultative microbes. According to RPI, their microbe mixture includes microbes that work under both aerobic and anaerobic conditions which may be an advantage over relying on indigenous microbes to adapt to the large swings in the subsurface environment after CBI is injected.

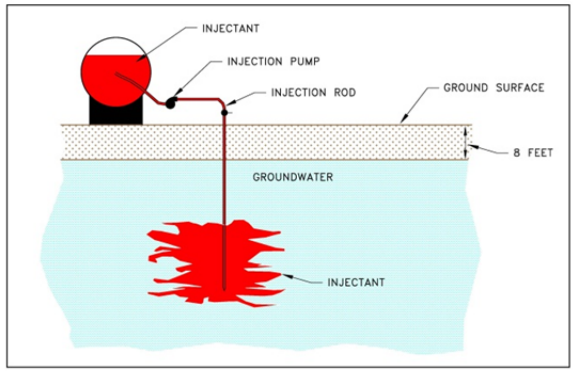
8. A FEW WORDS ON RADIUS OF INFLUENCE

Environmental engineers have long relied on estimates for the radius of influence (ROI) for most remediation methods. Regulators generally require ROI estimates before approving a remediation system, mechanical or otherwise. We love putting ROI circles on drawings, carefully considering how much overlap should be used and then basing our system designs on the area encompassed by the ROI circles. In reality, ROI is a nebulous term. But using an ROI at least provides some estimate of the volume of media we expect to influence. Nevertheless it's just that; an estimate. When we begin putting too much reliance on an assumed ROI, we often run into trouble; especially with injectates.

With injectates some people assume, or at least represent visually in drawings, that the entire interconnected pore space of a given volume is replaced by the injectate. A few simple calculations confirm significant quantities would be necessary to completely replace an effective pore volume for a single injection point[5]. Using the two foot injection interval from our previous calculations, we begin to get an idea for exactly how much injectate would be required in various soil regimes, as shown on the following graph.



Regardless of the product injected, injections use significantly fewer gallons than would be required to completely replace the effective pore volume. But most drawings depicting conceptual injectate flow paths show unrealistically large volumes of injectate. The drawing to the right is an example. While the drawing is not-to-scale, the drawing makes it appear visually that the injectate itself displaces the liquid represented by the area shown in red. If we use a reasonable scale on the drawing (I assumed the depth to water was 8 ft. to set the scale), the effective pore volume represented by the volume in red varies from roughly 1,500 gallons (clay) to over 8,000 gallons (sand). That would be a huge amount of injectate for a single injection location! Based on our experience, it appears the injectate likely disperses in a much thinner, interconnected, random, web-like pattern. This will be discussed in more detail below.



9. PRACTICAL CONSIDERATIONS FOR A SUCCESSFUL CARBON-BASED INJECTION PROJECT

Based on our experience, any injectate can fail if there are deficiencies in any of the following areas:

1. Data collection,
2. Design,
3. Installation.

9.1 Data collection and design

To properly design any injection program, whether using CBI, in-situ chemical oxidants (ISCO), Fenton's, or any of a long list of available injectates, it's often necessary to delineate the subsurface conditions at a site more fully than many consultants or regulators are accustomed to doing. This detailed information not only will help to ensure the project's success but will help to ensure proper placement and injectate dosing, potentially saving a considerable amount of money. Among other important information, data collection for injectates will include fully identifying the source, nature and occurrence of contaminants, properly identifying the subsurface geologic and hydrogeologic conditions and identifying existing preferential pathways. Collecting soil samples below the water table to estimate the submerged contaminant mass is vital to properly calculate the injectate dosing.

Due to budget constraints or inexperience with injectates, many regulators and clients will not agree to the increased site characterization needed for proper design. Recognizing this deficiency, RPI provides free in-house analytical services for projects using BOS-200® as they know that insufficient data collection can easily translate into project failure. If a project fails, for whatever reason, it's unlikely the consultant or regulator will consider using their product, or possibly any injectate, on future projects. With injectates you typically get only one or two chances, unlike SVE or air-sparging where failure in the short-term is often overcome by leaving the system running for a longer duration.

Identification of LNAPL is critical to the success of any remediation project. If LNAPL migrates, any remediation method can be rendered ineffective. All potentially migrating LNAPL must be addressed either deliberately in the design of CBI itself or by using CBI in conjunction with other methods such as free-phase product removal to reduce the saturation risk of the LNAPL prior to injection of CBI.

9.2 Installation equipment

Once the site has been properly characterized and the design completed, the next – and possibly most important – step is delivering the injectate into the subsurface. The direct-push equipment used to deliver the injectate is typically available in most areas since it's the same equipment used during the assessment phase. If the direct-push equipment used to collect soil samples is capable of reaching the depths required for sampling, it most likely will reach the depths required for injection. In most cases, the direct-push equipment used for the injection is owned by the injection contractor. This isn't critical, however, since most local direct-push contractors need very little additional training to successfully assist in the injection if overseen by a knowledgeable injection foreman. This enables local resources to be used, saving money and enhancing the project through local knowledge.

There are several essential components to the injection system. This specialty injection equipment (including injection tips, injection rods, powder transfer and mixing equipment, injection pumps and hoses) typically is not available locally but easily can be mobilized to the project site.

Wanner Engineering's Hydra-Cell® diaphragm pump. (Used with permission: Wanner Engineering, Inc.[7])

Injection tips, located at the bottom of the hollow-injection string, must be properly designed to deliver sufficient exit velocity of the injectate while minimizing flow restrictions that might adversely affect the injectate delivery flow rate. Achieving this balance is especially important since we're injecting a suspended solid, not a chemical solution, and suspended solids will drop out of suspension or be filtered out by the formation if the injection flow rates are too slow.

The injection string must be of robust design with sufficient wall thickness to withstand the rigors of the constant pounding of the probe hammer but with sufficient internal diameter to allow high injectate flow rates. In tight formations it's important to recognize that smaller outside diameter probe rod may not necessarily penetrate better than larger diameter probe rod as much of the driving force may be lost due to rod flex and distortion.

Proper injection pump selection is also critical to a successful project. Piston-pumps may be required and even desired with certain very tight formations but will generally supply insufficient flow rates for most other formations. Also, activated carbon is very abrasive and can quickly render some pumps unusable.

Activated carbon is generally sold in 50 to 55 lb. bags or in 1,000 to 2,000 lb. super sacks. Some contractors purchase product in 50 lb. bags, cut the bag open at the project site and then manually dump the product into a mixing tank located on an open trailer. Since the consistency of the product is similar to talcum powder and has a specific gravity of around 30 pcf, there is a tendency for the product to become airborne. This requires the contractor wear a respirator and Tyvek® suit. Without care, the dust can affect people in the vicinity of the project not wearing the proper personal protective gear and enter nearby building and residential ventilation systems. As with most any dust, an explosive hazard can be created under the right conditions. The use of 50 lb. bags also makes accurate measurement of the product introduced into the mixing tank difficult and limits the use of the injection equipment during freezing or windy conditions since the equipment must be located on an open trailer or open truck.

These shortcomings can be largely overcome by specialty material handling and dust suppression equipment designed to allow the use of 1,000 lb. supersacks instead of 50 lb. bags, such as the equipment available through Enviro-Equipment, Inc.[2] Enviro-Equipment, Inc. manufactures and leases injection equipment which uses CleanInject™ technology, a patent-pending injection system designed to quickly transfer, mix and inject activated carbon-based products while also minimizing dust. Their system includes all of the powder transfer, material weighing, mixing, dust suppression, injection pumps and direct-push tooling needed for most jobs and fits inside a 16 ft. long enclosed cargo trailer. The trailer can be pulled using a conventional pickup and is operated by one person, enabling direct-push contractors and consultants to provide injection services in a project area with mostly local resources.

9.3 Injection procedures

With the proper equipment and at least one well trained injection foreman, CBI can be injected with as few as two people. On smaller jobs, a third person is desirable to assist in setup and teardown, backfill holes and help mobilize equipment to the site. On larger jobs, once the equipment is set up, a third person will rarely increase productivity significantly. If 50 lb. bags of product are used, the injection will likely require additional personnel to assist in product handling.

The injection foreman must thoroughly understand the project goals, including the anticipated subsurface conditions. In tight soils, backflow preventers and multiple injection rod strings may be required to allow the injected slurry pressures to stabilize in the formation. With the proper equipment, CBI can be installed in freezing conditions, but special care must be used to ensure all injectate delivery equipment outside the enclosed injection trailer (hoses, injection rod, injection tips, backflow preventers) doesn't freeze. Also, injection personnel must be extremely careful working with fluids and steel in freezing conditions. Injections are not recommended with exposed injection trailers during freezing weather as significant damage can occur to the pumps and mixing equipment.

Injectate surfacing should be avoided whenever possible. In our experience, it's possible for CBI injectate to surface even when small volumes, such as 40 gallon shots, are injected under high-pressure, high-flow conditions. We've experience surfacing as far as 30 ft. from the injection location, even while injecting at depths of 20 ft. below surface. With some injectates, surfacing is a potential safety issue due to the generation of excessive heat and combustible vapors, potential exposure of oxidants or vapors to nearby people and potential damage to structures due to the corrosive and exothermic nature of some of the oxidants[8]. Since CBI is non-toxic, surfacing is more of a nuisance than anything and surfaced CBI can be easily and quickly captured with a shop-vac or small vacuum-trailer. In certain areas, it may be desirable to pressure wash the area to remove unsightly carbon residue.

Injectate surfacing can often be avoided with practice. Injectate pressure signatures during the injection delivery may give clues that injectate surfacing is about to occur. It's important for field personnel to be vigilant and monitor the site for injectate surfacing anytime the pump is actively injecting CBI. Unlike some oxygenated compounds that create exothermic reactions after injection, we generally don't see CBI surfacing after the injection pump is turned off and the subsurface pressures have been relieved.

As with any injectate delivered using HF/HP pumps, the injectate will flow primarily in existing preferential pathways, or fracking will create new preferential pathways. This is desirable since groundwater will now flow preferentially through these pathways, forcing contaminated groundwater to come into contact with the injectate. This need to create preferential pathways is why it's critical to use properly designed pumps sufficient to overcome the overburden and pore pressure encountered at the injection depth. Low flow rates will often result in injectate surfacing around the injection rod, especially if the shallow portion of the injection hole was previously daylighted to expose potential subsurface utilities and the opening was not properly sealed after daylighting. Our experience suggests inadequate pumps and injection procedures will doom most any injectate.

Mixing dry activated carbon can be a messy job. The CleanInject™ system helps eliminate dust like this when working with CBI.[2] (Used with permission: Norwegian Research Council.[1])

9.4 Post injection

In addition to cleaning up surfaced or spilled injectate, it's often necessary to remove injectate from impacted groundwater monitoring wells. This can be accomplished with a vacuum truck connected to a stinger (a small diameter pipe, often made of PVC), inserted near the bottom of the impacted well. In some cases it may be necessary to introduce clean water to the well, surge the well with a surge block to assist in removing AC from the sand pack, and then followed by removing the CBI using the vacuum truck connected to a stinger. This process may have to be repeated several times on significantly impacted wells. In some cases, it's best to simply replace the impacted well by installing a new well nearby. You may also find CBI in water samples collected even from newly installed wells. This may be due to the well intersecting CBI residing in frac zones and preferential pathways.

10. COMPARISON OF CARBON-BASED INJECTATES TO OTHER INJECTATES

Many chemical oxidants and other injectates have a relatively short useful life. Since most of these injectates rely on chemical reactions, they often are ineffective after a very short time, typically 60 to 90 days. CBI on the other hand does not react and, unless chemically saturated (spent), will remain in-place indefinitely. CBI injected into the subsurface remains available to remediate future releases or, possibly, LNAPL sources not identified during the assessment phase.

CBI is safe, non-toxic and will not react with or destroy subsurface structures such as pipes or tanks. Unlike <u>any</u> other currently available product or system, CBI can be injected <u>prior to</u> a release and could conceivably be installed as a protective barrier around drinking water wells (well-head protection) or as a release barrier beneath existing or newly constructed liquid waste structures. If liquids leak from the waste structure at some point in the future, the previously injected CBI might help limit migration of the contaminants and minimize impacts to groundwater or other critical receptors.

In situations where AC without the amendment of proprietary (patented) ingredients is sufficient, CBI can be used more liberally due to its low cost. This makes it economically feasible to use CBI for a wider range of applications such as marine sediment remediation, well-head protection and sensitive receptor protection. CBI also could be placed preemptively in excavation areas known to be impacted by petroleum contamination. This could be a low-cost method to protect workers and minimize transference of the contaminants into the environment during excavation.

In most cases we've found the use of CBI for site remediation is significantly cheaper than most conventional remediation methods such as air-sparge, soil vapor extraction, dual-phase extraction and dig-and-haul. With the exception of dig-and-haul, all mechanical systems require repeated site visits, significant power consumption, long-term monitoring and significant site disruptions. Further, all of these technologies rely on transferring the contaminants to another media or location. CBI works in-place and, like most injectates, is a “green technology.”

We’ve also found that CBI can be used in sites with challenging geologic conditions such as fractured bedrock and glacial deposits. These geologic settings don’t often lend themselves to the use of conventional remediation technologies since they’re not easily excavated or drilled. In some situations, however, it’s possible to inject or distribute CBI into the voids, allowing the CBI to sequester the contaminants, eliminating the need to excavate or drill.

With ever increasing budgetary constraints, the use of CBI appears poised to quickly gain widespread acceptance but, like other remediation technologies, CBI is not applicable to all sites. In some cases, we’ve found CBI is best applied in conjunction with other technologies. Based on the success rate of CBI so far, and considering the ever increasing budget problems, it’s likely the use of CBI will expand considerably in the near future.

11. BIBLIOGRAPHY / NOTES

1. Norwegian Research Council, "Sediment Remediation Through Activated Carbon Amendment", NGI Report No. 20081057-1, April 2011.
2. Enviro-Equipment, Inc. (EEI), 10120 Industrial Drive, Pineville, NC 28134 (www.enviroequipment.com) manufactures and distributes specialty mixing and injection equipment based on CleanInject™ technology (www.CleanInject.com). EEI also distributes GR-320-IRC™, a pulverized activated carbon with a select gradation which makes their product amenable to slurry injection.
3. General Carbon Corp., 33 Paterson Street, Paterson, NJ 07501
4. Calgon Carbon Corporation, "How much adsorbate can the carbon adsorb?", online http://www.calgoncarbon.com/carbon_products/faqs.html.
5. For purposes of the calculations used in this paper, I assumed only the volume associated with a single injection point and no influence from adjoining points. Therefore, I arrived at the total volume by the following equation: Total Volume = $\pi \times ROI^2 \times T$; where ROI = radius of influence and T = injection interval. In practice, if injection points are spaced equal to their ROI, the area between the injection points will be influenced by all the surrounding injection points. A more accurate representation of the influence from each injection point might then be to calculate volumes using $ROI^2 \times T$. All this is theoretical at best and is not necessarily pertinent to the broader discussion of this report.
6. The calculations presented are intended to provide a rough estimate of the capacity of the activated carbon to adsorb contaminants. The actual adsorptive capacity of the carbon will also be affected by, among others, the type and source of activated carbon, groundwater chemistry and the weathering of the contaminants in-place. These calculations also assume the injected AC is available to adsorb the entire contaminant mass used in the calculations.
7. Wanner Engineering, Inc.. 1204 Chestnut Ave., Minneapolis, MN 55403
8. In Situ Remediation Reagents Injection Working Group, "Technical Report: Subsurface Injection of In Situ Remedial Reagents (ISRRs) Within the Los Angeles Regional Water Quality Control Board Jurisdiction", September 16, 2009.

12. ABOUT THE AUTHOR

Tom Lewis, P.E. is president of Resource Geoscience, Inc. (www.rgicos.com) a Colorado based environmental consulting and contracting business celebrating 20 years in business. Lewis was lead-inventor of the patent-pending CleanInject™ system and is a graduate of the Colorado School of Mines.