Use of Degradable, Non-Oxidizing Biocides and Biodispersants for the Maintenance of Capacity in Nutrient Injection Wells

by
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Abstract:

Fouling of water supply wells is a common problem, dating from the time humans started using groundwater resources for water supply. In the groundwater remediation field, fouling of recovery and treatment systems has been a similarly common operating problem. Thus it is not surprising, with the increased use of in-situ remedial methods, that fouling of in-situ treatment units is becoming a major design concern. In-situ treatment units include recovery wells, injection wells, recirculating wells, flow-through treatment cells, and in some cases, geologic formations themselves. The very effectiveness of these units depends greatly upon retention of permeability or hydraulic capacity. Capacity can be dramatically reduced due to fouling by naturally occurring inorganic precipitates or by microbial deposits.

One of the least surprising instances of fouling of an in-situ treatment unit involves various bioenhancement techniques, where nutrients are injected with the intention of enhancing certain types of bioactivity and subsequent biodegradation of contamination. The data presented in this paper are derived from experience at remedial sites where bioenhancement activities have been self-defeating by causing a loss of permeability in injection wells, surrounding geological formations, or down-gradient recovery or recirculation wells. In these cases, non-oxidizing biocides, bio-dispersants, saponification agents or other additives have been applied to retain permeability in the hydraulic “bottlenecks” of these systems, such as injection wells and surrounding formations. Data collected from such applications shows that proper characterization of fouling mechanisms and subsequent application of well-designed deposit control programs can eliminate operational problems associated with fouling arising from bioenhancement.

This paper introduces the key concepts in deposit control practices as they apply to fouling of in-situ treatment units. It provides an overview of the various agents and techniques used in such deposit control programs. Regulatory and design issues are discussed, and subsequently illustrated by a series of brief case studies.

Introduction

Fouling of water treatment equipment by inorganic and microbial deposition is a common and widespread operating and maintenance challenge. The annual expense incurred in controlling fouling of drinking water systems, boilers, cooling water systems, irrigation systems and wastewater systems exceeds billions of dollars worldwide. In the groundwater remediation market in the United States, the vast majority of expenditures go to operations and maintenance costs, with control of fouling being a major maintenance cost at many sites (API, 1990). The authors of this paper have specialized exclusively in solving fouling problems in groundwater remediation systems, with a combined experience of about forty years in this area. According to their experience, fouling occurs at a minority of sites where groundwater is treated, but at those sites where it is occurring, controlling fouling is always a significant portion of operations costs.

Inorganic deposition or microbial growth comprises all fouling in groundwater remediation systems. Inorganic deposition usually consists of iron-related deposits or hardness scales. Iron-related deposits typically involve both iron and manganese, naturally occurring, which is soluble in the reducing conditions found in most aquifers, but which easily oxidized and thus precipitates, when the oxidation-reduction potential of groundwater increases due to certain ex-situ or in-situ treatments. The oxidation of iron and manganese may be a simple chemical oxidation or it may be microbially mediated, yielding energy for certain iron-related bacterial species. Thus it is not uncommon to find a significant microbial component in iron-related deposition. Hardness deposition consists primarily of naturally occurring calcium and manganese carbonates, which are dissolved to saturation (or equilibrium) in groundwater at some ambient pH in-situ, but which precipitate due to changes in pH which may occur upon treatment. Microbial deposition is rarely associated with hardness deposits.

While microorganisms are widely known to be pervasive in groundwater, the formation of concentrations of microbial consortia associated with troublesome fouling usually involves the exposure of naturally occurring microbial species to a sudden increase in substrate or growth-limiting nutrient. Examples of this phenomena would be conditions in an oil-water separator, resulting from aeration and mixing occurring during pumping, or those occurring around a nutrient injection well during in-situ biostimulation.

Biofouling problems in environmental systems tend to be due to 1) slime forming bacteria, 2) iron-related bacteria or 3) biologically stabilized emulsions. Biofouling problems may manifest themselves in remedial systems in many ways. Examples include:

- Slime that blinds bag filters and reduces service life
- Emulsions that clog coalescing plate oil-water separators
- Deposits that plug the surface of activated carbon filters
- Slime and encrustation of well screens and subsequent loss of capacity
- Deposits in pumps, conveyance pipes, and transfer equipment
- Flow restrictions in treated water reinjection systems

This paper provides an overview of methods used to control biofouling in the groundwater remediation field. It includes a description of common characteristics of biofouling in these applications, chemicals and techniques that have been applied for control, and provides several case studies for illustration.

Basic Microbiology Relevant to Site Remediation

Both bacteria and fungi can achieve biodegradation of organic materials in natural environments. These two types of organisms utilize different chemical pathways for degradation, and thrive in slightly different environmental conditions. While fungi and bacteria commonly coexist in natural environments, the optimum pH for fungal growth is lower than that for bacteria. While bacteria are certainly the dominant biodegraders in conditions found at remedial sites, both types of organisms can contribute to biofouling.

Bacteria that cause biofouling in remedial systems tend to be indigenous, except in cases of bio-augmentation, which involves the introduction of cultured or “manufactured” contaminant-targeted microbial species. Unlike certain fungi, all bacteria are single-celled organisms. They range in size from approximately one to five microns. Bacteria reproduce by binary fission, in which a mature cell splits into two new cells. For many species found at remedial sites, the time required for a cell to divide, or generation time, is as short as thirty minutes. At this rate a single organism can become ten million cells within 12 hours. This exponential growth can produce huge amounts of biomass in a short amount of time.

Bacteria require an energy source and nutrients (primarily carbon-based molecules) to grow, and are thus classified based upon their energy source and nutritive requirements. Bacteria which derive energy from light are termed phototrophs, and those that derive energy from either organic or inorganic molecules in their environment are called chemotrophs. Those which obtain carbon from carbon dioxide are autotrophs, and those which obtain carbon from organic molecules are called heterotrophs. Combining these terms allows the classification of all bacteria into four categories, as illustrated in Table I (adapted from Baker and Herson, 1994).

Table 1
Classification of Micro-ororganisms

Classification	Energy Source	Carbon Source
Photoautotroph	Light	Carbon dioxide
Photoheterotroph	Light	Organic carbon
Chemoautotroph	Inorganic chemical	Carbon dioxide
Chemoheterotroph	Organic carbon	Organic carbon

The most important class of bacteria, in terms of bioremediation, is clearly the chemoheterotrophs, which use organic compounds as both an energy and carbon source for cell synthesis. In terms of biofouling, however, both types of chemotrophs are important, and in rare cases where treatment units are exposed to light (as in above-grade translucent treatment units) photoheterotrophs and algae can become important contributors to fouling problems.

Finally, in considering the impact of chemoheterotrophs, in terms of both bioremedial and biofouling considerations, one must understand the various metabolic modes used by these organisms. Bacteria degrade organic molecules through a series of microbially mediated reduction-oxidation (redox) reactions, in which one compound is reduced (gains electrons) and another is oxidized (loses electrons), and in the process, energy is liberated. Bacteria produce enzymes which catalyze these reactions in order to harvest energy from the degradation process, and utilize adenosine triphosphate (ATP) to gather the energy, and release it later when needed elsewhere for cellular activity. The metabolic processes used by various bacteria to degrade organic molecules are categorized by the type of compound which initially is oxidized (electron donor) and the compound which is finally reduced, referred to as the terminal electron acceptor. Table 2 (adapted from Baker and Herson, 1994) shows this categorization.

Table 2
Classification of Metabolic Sequences

Type of Metabolism	Electron Donor	Terminal Electron Acceptor
Respiration	Organic or Inorganic Compound	Inorganic Compound
Aerobic		Oxygen (O_2)
Anaerobic		Fe^{+3}, SO_4^{-2}, CO_2, NO_3^-,
Fermentation	Organic Compound	Organic Compound

While fermentation has been shown to play an insignificant role in bioremediation, respiratory metabolism is a very important process in terms of both bioremediation and biofouling. The type of respiration that occurs at remedial sites is a function of the available oxygen, among other factors. A lack of oxygen favors bacteria that use pathways involving anaerobic respiration, and if inorganic compounds are also absent, fermentation. Bacteria utilizing aerobic respiration metabolize more organic mass than those using anaerobic processes, and so, for purposes of degradation of organic contaminants at remedial sites, aerobic processes are most important and much more commonly employed. Research over the past ten years, however, shows that anaerobic processes may be more capable of degrading certain halogenated (highly oxidized) compounds, as well as nitroaromatic and aminoaromatic compounds, which include certain pesticides and energetic compounds (Liss and Baker, 1994).

Availability of oxygen in groundwater is related to a characteristic of aqueous environments called the redox potential, denoted Eh. This parameter expresses the activity of electrons in a solution, just as pH expresses the activity of protons. Eh can be measured as the potential for a redox reaction in relation to a standard hydrogen electrode, and is expressed in millivolt units. While oxygen is available as O_2 when redox potential is high (>800 mV at pH 8), it is reduced to O^{-2} (as in H_2O) at lower Eh, thus forcing microbial consortia to utilize a variety of other inorganic compounds as terminal electron acceptor. For example, at Eh of 770 millivolts, ferric iron, or iron III, can serve as terminal electron acceptor thus being reduced to ferrous iron, or iron II (Deutsch, 1997). The oxidized and reduced inorganic species involved in a redox reaction (such as ferrous and ferric iron) are also referred to as a redox pair. Table 3 (adapted from Liss and Baker, 1994) shows the relationship between various redox pairs, associated respiratory processes, and redox conditions.

Table 3
Redox Conditions Versus Favored Respiratory Processes

Redox Pair	Respiratory Process	Redox Conditions
O_2, / H_2O	Aerobic Respiration	Oxidized
Fe^{+3} / Fe^{+2}	Iron Reduction	↓
NO_3^- / N_2	Denitrification	↓
NO_3^- / NO_2^-	Nitrate Reduction	↓
SO_4^{-2} / H_2S	Sulfate Reduction	↓
CO_2 / CH_3COO^-	Methanogenesis/Fermentation	↓
CO_2 / CH_4	Methanogenesis	Highly Reduced

While anaerobic respiratory processes may not be important in most bioremediation applications, certain anaerobic microbial processes are important in terms of biofouling. Redox pairs shown in Table 3 are by nature sensitive to redox potential. Of note, in terms of fouling, is that for some redox pairs, solubility of the two species involved are different. For example, ferric iron salts are relatively insoluble while ferrous iron salts are quite soluble. Also, sulfate salts are generally soluble, while hydrogen sulfide is a gas with limited solubility. Thus microbial activity of certain types can create insoluble inorganic deposits (or gases) that can be problematic.

Fouling Associated with Bioremediation Applications

Fouling in bioremediation systems can involve precipitation of naturally occurring inorganic compounds or excess growth of microbial masses. In some cases inorganic precipitation is associated with microbial growth as is the case with bacterial consortia associated with high iron or sulfate concentrations in groundwater.

Inorganic precipitation usually involves precipitation of iron oxyhydroxides or hardness salts. Iron deposition occurs due to the oxidation of iron from the ferrous to the ferric state, with the resulting formation of insoluble iron (III) hydroxide. Newly formed iron (III) hydroxide can remain mobile as submicron colloidal particulate, but usually agglomerates in time, and subsequently precipitates in above grade treatment vessels, or sorbs on soil surfaces in-situ. Hardness salts usually precipitate as a result of pH changes which are common in above-grade treatment systems involving aeration, which also desorbs carbon dioxide, typically increasing pH about 1 unit. Such pH changes are unusual in in-situ bioremediation projects. While the authors have studied hundreds of remedial sites with inorganic fouling in ex-situ treatment equipment, they have received few reports of such precipitation in-situ, where oxidizing agents have been added. This may be that precipitation is so distributed that its impact on permeability is rarely observed.

Biofouling, both in-situ and ex-situ, generally involves the development of a biofilm which is detected due to its effect on permeability or hydraulic capacity of the aquifer, injection/recovery well or treatment equipment. Bacteria in water systems are either free-floating, also called planktonic bacteria, or attach themselves to surfaces, and are then termed sessile bacteria. Sessile bacteria have appendages which allow them to adhere surfaces. Most of the organisms important in bioremedial applications are sessile (This is why most biotreatability studies are typically done using soil samples rather than groundwater samples, as the latter would contain mostly planktonic organisms). A thin layer of sessile bacteria forms the basis for development of a thicker biofilm, usually composed of a consortium of many different species.

Within a biofilm, bacteria secrete complex sugars known as polysaccharides during their metabolism process. These polysaccharides have a high affinity to adsorb water into their matrix. The polysaccharide and water complex (or biopolymer) can exceed the mass of the bacterial cells by more than 100 times. This biopolymer provides a protective environment that promotes rapid growth of bacteria. Chemically, the polysaccharide also has an affinity for divalent metals. Dissolved calcium, magnesium, and iron react with carboxyl groups on the biopolymer. Eventually, a thick film consisting of bacteria, bacterial by-products, and entrapped minerals accumulates. This accumulated mass is known as biofilm. Depending on ambient water conditions, the surface of the biofilm can support aerobic bacterial activity, while the lower layer of the biofilm is typically deprived of oxygen, and supports development of anaerobic bacteria. These anaerobic bacteria produce troublesome metabolism by-products, including organic intermediates, sulfur compounds, organic acids, and sulfuric acid.

Biofouling in bioremediation projects is often the unavoidable consequence of an effort to stimulate the growth of degrading organisms, and the difficulty in focusing this stimulation on the preferred organisms. The distinction between successful biostimulation and biofouling lies in the extent of operations impediment posed by the biomass generated. When biofilms grow to the extent that flow required to deliver substrate, nutrients or oxidizing/reducing agents is hindered, further biostimulation becomes impossible and self-defeating.

In the authors' experience, the most common point of biofouling at in-situ remediation projects is in the well pack and aquifer surrounding reagent injection wells. Such biofouling is particularly acute when injection is continuous or regular, with little time between injections. Depending on the redox conditions of the injected fluids, changes in redox conditions in the aquifer around an injection point can also contribute to the deposition of redox sensitive inorganic species, particularly iron.

Another common location for both microbial and inorganic deposition, at sites that involve groundwater recovery, is the well pack and well screen of recovery wells. If recovery pumps utilize a control system where pumps cycle on and off at different elevations, oxygenation of the aquifer occurs near the well, causing oxidation of iron, if present. Lower pressure upon groundwater, as it approaches the cone of groundwater table depression formed at a recovery well, can result in the release of carbon dioxide, and associated pH change and precipitation of hardness salts. Exposure of groundwater to air in and around the well bore can stimulate the growth of aerobic organisms, generating biofilms. Finally, iron-related bacteria are prevalent, near recovery wells where redox conditions favor microbially-induced oxidation of iron. Iron bacteria are filamentous organisms that oxidize inorganic ferrous iron as a source of energy and deposit oxidized iron ($Fe(OH)_3$) in their bacterial sheath. *Leptothrix, Crenothrix, and Gallionella* are fairly common species of iron bacteria encountered in groundwater treatment systems. The basic reaction of these bacteria is given below:

$$Fe^{++} \text{ (ferrous)} + \text{oxygen} \quad > \quad Fe^{+++} \text{ (ferric)} + 1\ e^{-}$$
$$Fe^{+++} + 3\ H_2O \quad > \quad Fe\ (OH)_3 + 3\ H^{+}$$

The electron released in this process is utilized by the bacterium for energy production. Ferric hydroxide is adsorbed into the bacterial sheath. The evolution of hydrogen further depresses pH, which in turn increases the dissolution rate of minerals.

The various types of fouling discussed in this section can be detected by visual inspection (among other methods) in ex-situ applications, but fouling in-situ can only be detected by regular measurement of groundwater flow and specific capacities of recovery and injection wells. In addition, measurement of various parameters pertaining to groundwater chemistry, at sample locations upgradient (or upstream) and downgradient (or downstream) of locations where fouling is occurring can provide valuable clues as to the mechanisms causing deposition.

Methods of Control of Biofouling

Various chemical methods for controlling inorganic fouling in remedial systems have been successfully applied since 1990. Blended deposit control agents, formulated specifically for groundwater remediation applications, have been applied at hundreds of sites by the authors. However, methods for successfully controlling biofouling are less common in the literature relating to groundwater remediation, and in the experience of the authors. A small number of applications, including those case studies discussed below are instructive.

Many of the commonly employed methods for biofouling control in remediation wells are derived from methods historically used with water supply wells. While some of these methods may be useful in remedial applications, groundwater remediation systems are prone to different, and more severe, biological problems than those encountered in water supply wells. This is due to the fact that contaminated groundwater has more complex chemistry and microbiology than drinking water sources. In addition, chemicals used in rehabilitation of water supply wells (in the US) must be certified for drinking water use (compliant with Standard 60 written by the National Sanitation Foundation, or NSF). This requirement does not apply to remedial well applications, allowing the use of much more effective products. There are many such agents available that have very favorable toxicological profiles, but for a variety of reasons, do not carry NSF certifications. For the reasons described above, many of the well rehabilitation and deposit control techniques that have been widely applied to municipal water supply systems are ineffective or inappropriate in remedial applications.

Two notable examples are the use of oxidizing biocides and polyphosphate-based sequestering agents, both widely used in rehabilitation of water supply wells. Oxidizing biocides, which include sodium hypochlorite (bleach) and chlorine dioxide may be effective, if properly applied, in temporarily eliminating biomass. However, their use in remedial applications, where high concentrations of redox sensitive depositing species are present, is problematic. For example, where ferrous iron is present in groundwater, these biocide products will necessarily result in deposition of all iron present, solving one problem (biofouling) but creating another (deposition of iron). Polyphosphate-based sequestering agents are widely used to dissolve inorganic deposits. While these products do aid in sequestering iron and hardness deposits, they can enhance ongoing biofouling, because they degrade to orthophosphate, a limiting nutrient in many groundwaters. In remedial applications, more challenging and complex water chemistry, and the potential to use products that are not NSF-approved, combine to allow the use of much higher performance deposit control chemicals.

Well rehabilitation techniques currently used in the remedial field are also derived from those developed in the water supply market. They involve a significant effort in aggressive physical swabbing and surging using large, expensive equipment. Such efforts are necessitated due to the use of relatively ineffective chemical agents, which are limited to those that are NSF-approved. The choice of high performance cleaning and preventative agents, which are not NSF-approved, and not necessary in remedial applications, obviates the need for expensive and aggressive physical cleaning methods, thereby reducing overall costs.

High performance chemicals which have been recently and successfully applied for rehabilitation of fouled wells at remedial sites include non-oxidizing biocides, bio-dispersants, chelating acids and saponification agents. Most of these products are available in proprietary blends that have been developed for site-specific applications, based upon the operating characteristics and nature of fouling at a particular site. Biocides are certainly the most effective way of eliminating biofouling, but the application of biocides in-situ involves regulatory hurdles that vary from state to state. Biocides must be registered federally, and in any state in which they are used, according to the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA). Bio-dispersants, chelating acids and saponification agents are less burdensome to apply, from a regulatory perspective, as they are not subject to the FIFRA requirements.

Non-oxidizing biocides have been used by the authors to control biofouling at hundreds of remedial applications since 1990. These biocides are chosen for their effectiveness on a broad range of microbial species, favorable toxicological profile, rapid degradation characteristics, chemical characteristics which make them non-reactive with organic contaminants commonly present, and safe to operations personnel and treatment equipment. The most effective biocide products are blended with non-biocide ingredients which enhance penetration of dense biofilms, and help disperse non-living biomass. Biocides are typically applied in periodic high-dose (“slug”) applications, rather than continuously at lower doses. This avoids adaptation of the microbial consortia, which involves the death of the most sensitive species, yielding resources which enhance growth of more resistant species, resulting, over time, in a biomass resistant to the treatment. It also results in significant cost savings compared to continuous dosing. Alteration of the biocide used is also a common technique employed to avoid this adaptation process.

Bio-dispersants are non-biocidal surface-active agents which break up biofilms and cause them to “slough off” of surfaces to which they attach. They can be continuously applied or periodically “slug-dosed”. Since these products effectively mobilize solids, they can cause clogging in downstream and down-gradient locations, and this potential must be taken into account when designing proper application.

Chelating acids and other sequestering agents reduce biomass in two ways. First, they can be applied in a slug dose to create a low pH shock. Second, their ability to react with inorganics can help to mobilize inorganic components in biofilms, and prevent their “bio-availabilty”. Specifically, the authors’ have used iron sequestrants, under the right conditions, to control iron bacteria by reducing the presence of free ferrous iron.

Saponfication agents are caustic chemicals which react with bio-organic molecules to enhance their solubility, thus dispersing the polysaccharide slime constituting the majority of biomass. Saponification is the reaction by which soaps are made, creating molecules that are non-polar organic (and therefore water insoluble) on one end, but polar (water soluble) on the other end.

The chemical agents described above have been used to control biofouling of injection and recovery wells, as well as biofouling of ex-situ treatment systems. They have been used individually or in combination, depending upon the application, and have been applied in a variety of ways. At any particular site, the final long-term deposit control program has typically been derived by a series of adjustments in dose rate and feed points, with subsequent monitoring of pressure drops due to re-establishment of biofilm. In all cases involving deposition, treatment must be ongoing to retain hydraulic capacity of treatment units. At sites where well rehabilitation was performed, periodic rehabilitation is required. In other cases, a preventative program of regular chemical dosing can be developed. Case studies described below illustrate how biofouling control programs are site-specific

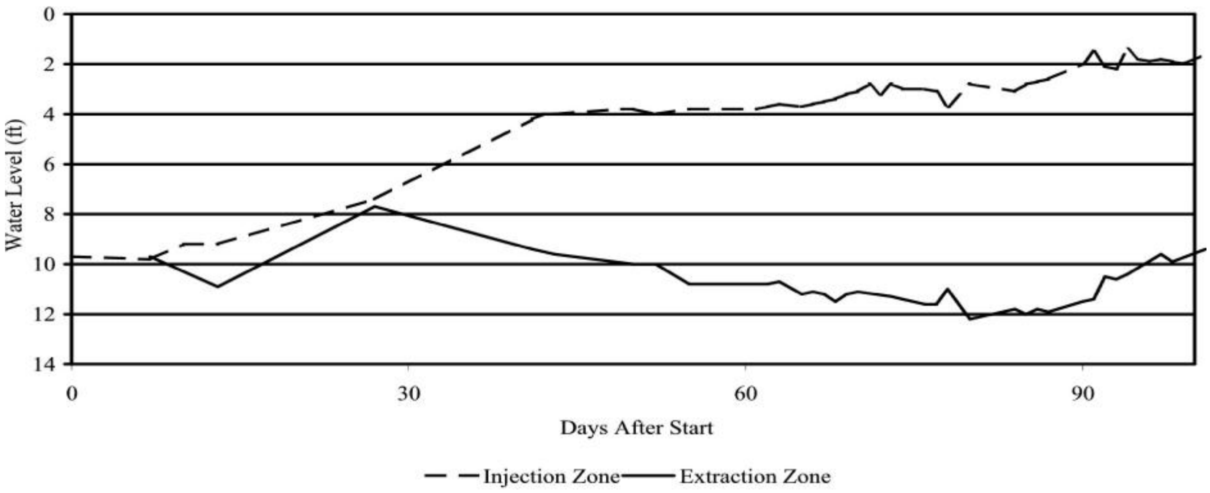
Case Studies

Three brief cases studies are described below, each involving in-situ biofouling at NPL listed Superfund sites. Additional information about these and other applications is available for interested readers.

Case Study 1: East Coast DOD Site

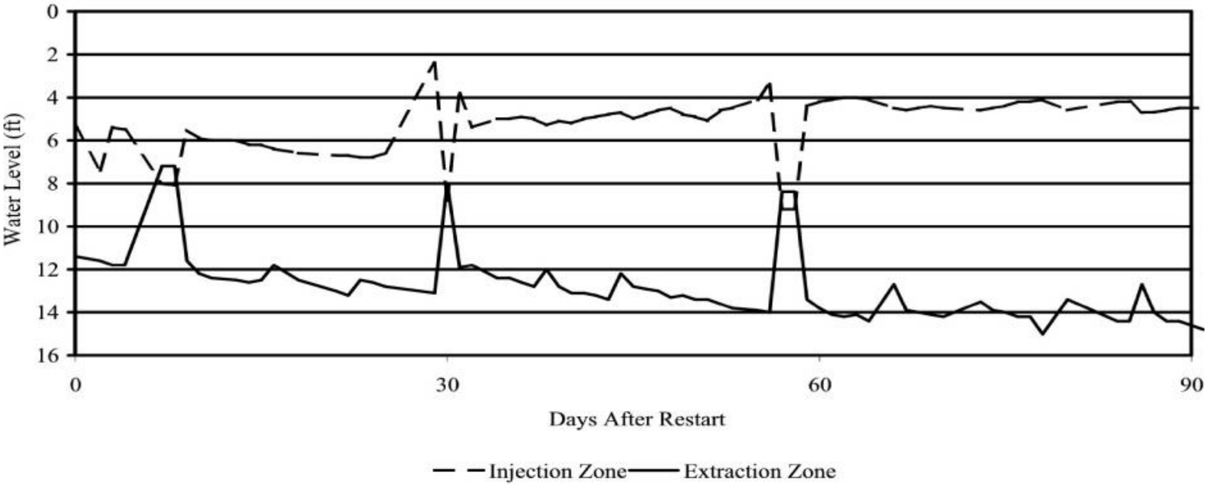
This site involves a large US Department of Defense installation that includes several locations where remedial activities are ongoing. The subject location had been contaminated with various chlorinated solvents. A major national consulting firm was hired to conduct a pilot test demonstrating in-situ reductive dechlorination, using a recirculating well, screened at two isolated elevations. While analytical data from the pilot test showed favorable degradation results, water levels in the injection zone began to increase precipitously within two weeks of operation, ultimately resulting in termination of the pilot test work. Figure 1 below gives water levels in the injection and extraction zones during this work. It was subsequently determined that microbiological fouling of the well pack and formation around the recirculation well had caused the permeability loss.

Figure 1
Water Level (Initial operation w/ no bioicide)



A second phase of pilot testing was planned, after initial investigations into alternative biofouling control methods. Redux B-T20, a non-oxidizing biocide was utilized to redevelop the well, and subsequent operation involved regular injections of B-T20. Subsequent data collection documented the effects of these injections. Of note was the fact that biocidal activity in the aquifer was limited to a certain radius around the well, with intended biodegradation occurring outside this zone, resulting in the maintenance of injection zone permeability, without deleterious effect to overall remedial goals. Figure 2 illustrates water levels in the second phase.

Figure 2
Water Level (Restart with biocide)



System operation after the restart of the pilot study involved monthly biocide soak of the recirculation well and well pack. The biocide feed was inadvertently lost about 26 days after the restart, after which a loss of permeability occurred, illustrating the bacteriostatic effects of the biofouling control program. A full-scale system has been in successful operation for several years now using regular B-T20 dosing.

Case Study 2: Long Island Superfund Site

This site involves a historic release of chlorinated solvents from an industrial facility. As is typical of Long Island geology, a sandy permeable aquifer lies under the site, and a public water supply well is located approximately 9,000 feet down-gradient. Three recirculating wells were installed to intercept groundwater, utilizing the UVB design, which involves groundwater recovery at a certain elevation, in-well induced air stripping for removal of VOC's, and recirculation to a different aquifer elevation. These ten-inch wells are nearly 400 feet in total depth, with the water table at about 55 feet below grade. Each well treats about 70 gallons per minute. One of the three wells went on-line in advance of the other two, but within a few weeks, fouling with iron and iron bacteria became evident. Video inspections of well screen showed orange filamentous growths characteristic of iron bacteria. Though iron levels are relatively low (100 to 500 ug/l), they are high enough, in conjunction with other groundwater quality parameters, to result in a significant iron bacteria problem.

Site operators and regulators initially opted to apply an iron deposit control chemical that contains only NSF Standard 60 certified ingredients, in this case a polyphosphate-based sequestering agent. As discussed earlier in this paper, limiting chemical choices to those with NSF certification limits possible ingredients to only a few moderately performing products, and thus results in a severe performance limitation.

Application of this deposit control agent was not effective, and well fouling became worse over time, requiring shutdown due to low flows within several months after start-up.

At this time, a thorough well redevelopment was performed and the well was restarted using Redux 601, a blended bio-dispersant comprised of a chelating acid and a polymeric dispersant. The chelating acid reacts with ferrous iron to reduce its bio-availability, and the dispersing polymer reduces the ability of biomass to adhere to well and soil surfaces. As of late 2007, all three wells have been operating successfully for nearly two years without downtime.

Case Study 3: New Jersey Superfund Site

This major New Jersey superfund site has the highest operating costs of any superfund site, approaching four million dollars annually. Various fouling problems plague the site's multiple recovery wells, which recover groundwater contaminated with chlorinated VOC's and certain heavy metals. Like many sites, fouling by iron and iron-related bacteria did not become serious until an initial operating period of about two years. On many sites, well fouling is not aggressively monitored, and gradual well fouling goes unnoticed, until target recovery rates simply are not achievable. Upon recognition that well fouling was occurring, extraction well redevelopment and pipeline cleaning has been required at least twice yearly.

Redux Technology became involved in 2005 and has since been developing well-specific deposit control programs for each well, in stepwise fashion. Initial efforts focused on improving well development procedures so that maximum specific capacities could be recovered in the regular redevelopment program. A multi-step well redevelopment procedure has shown the best results. The procedure developed to date includes the following steps:

- Physically remove accumulated debris via "hydroblast" or brush
- Acidify well with Redux 510, low corrosivity acid, for sixteen to twenty-four hours. This step dissolves the mineral portion of the biomass
- Surge well with surge block for two to four hours
- Airlift resulting debris
- Apply alkaline saponification treatment, for sixteen to twenty-four hours. This step removes residual polysaccharide "bioslime" deposits.
- Surge well with surge block for two to four hours
- Airlift any residual debris

In addition to an improved well redevelopment program, Redux has instituted preventative chemical additions for certain wells, eliminating the need for regular well redevelopment. For most wells, this has involved down-hole application of a small continuous dose of Redux 333, a high performance agent which contains an iron sequestering agent and a bio-dispersant. Project managers recently decided to expand the application of the preventative program to additional recovery wells.

Conclusions

Important issues discussed in this paper which should be re-iterated include:

- The exponential growth of bacteria can produce huge amounts of biomass in a short amount of time. This can result in sudden and surprising changes in the operating characteristics at sites with biofouling.
- Biofilm is the term for an accumulated mass comprised of bacteria, polysaccharide secretions, and inorganic particulates deposited within.

- Aerobic and anaerobic respiratory bacterial processes are the most important contributors to biofilm production.
- Certain types of microbial activity can create insoluble inorganic deposits that contribute to biofouling.
- Non-oxidizing biocides have been used to control biofouling at numerous remediation sites since 1990.
- Various non-biocidal methods of controlling biofouling have been successfully applied on a limited number of sites in the US recently.
- Dosing techniques play an important role in overall biofouling control program effectiveness and costs.

The pervasiveness of fouling of ex-situ treatment units in the groundwater remediation field is now well recognized by system designers. While there has been continued technology advances and increased popularity of innovative in-situ treatment methods in recent years, fouling in these application often goes unrecognized. This often results in increased operations costs as retrofit deposit control programs become required. A wider recognition of the potential for fouling and its operating complications is required, since design forethought can often greatly ameliorate the operating impact of these common operating problems. Along with the recent developments in the application of in-situ treatment programs, new chemicals and techniques have been developed which apply to fouling in this type of application. These new chemical products provide increased performance, and present lower toxicological impact than previously available alternatives. While applications data is not widely available in the literature, the number of in-situ applications with integral deposit control programs continue to grow.

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