Biological Fouling Control: Lessons from an In Situ Anaerobic Biodegradation System

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ABSTRACT: A study of an accelerated anaerobic biodegradation (AAB) system installed at Dover Air Force Base, Delaware to remediate groundwater contaminants is presented here. In order to maximize the efficiency of an AAB system, biofouling must be controlled. However, biofouling control methods must not interfere with the system's primary objective of contaminant degradation. The three current "primary" strategies are (1) hydrogen peroxide treatment, (2) application of anaerobic biocide to the injection wells, and (3) limitation of organic substrate in the groundwater recirculation components. Hydrogen peroxide treatments restored system flow after biofouling in the injection wells interrupted operations, but limitations of this treatment necessitate an alternative control method. Biocide application proved effective in increasing system flow rates, and lacked the concerns associated with hydrogen peroxide, but raised new and unique concerns. An ideal substrate injection rate is sought that will improve contaminant degradation while minimizing biological growth in the system's components. Further analysis of the system operations and the results of injection rate adjustments are required to determine if an ideal injection rate can be achieved. Despite concerns associated with biofouling, the selection of in situ AAB for remedial actions involving groundwater contaminants is still recommended.

INTRODUCTION

During the past decade, many pilot-scale and full-scale projects have demonstrated that, in situ, accelerated anaerobic biodegradation (AAB) effectively remediates a variety of groundwater contaminants (AFCEE, 2004). As the application of this technology spreads, biofouling is often cited as an obstacle to successful implementation of AAB. This paper documents strategies employed to control biofouling in a full-scale, in situ AAB system and presents lessons learned during 4 years of system operations.

In situ AAB is successfully treating chlorinated solvents that were historically released into the environment beneath Building 719, a mission-critical maintenance facility at Dover Air Force Base (DAFB), Delaware. Contaminants are attributed to engine-cleaning activities conducted in the building and include chlorinated ethenes (perchloroethene [PCE], trichloroethene [TCE], cis-1,2-dichloroethene [cis-1,2-DCE], and vinyl chloride). TCE concentrations as high as 21,000 micrograms per liter (µg/L) have been detected in shallow groundwater at the site. An AAB system was installed to remediate contaminated groundwater in the source area and minimize the continued contribution to the dissolved plume that extends approximately 1 mile downgradient.

The conceptual model for the system (Figure 1) is viewed as two interdependent components: one biological and the other mechanical. First, the biological treatment zone is established around the system injection wells where reductive dechlorination of contaminants occurs.

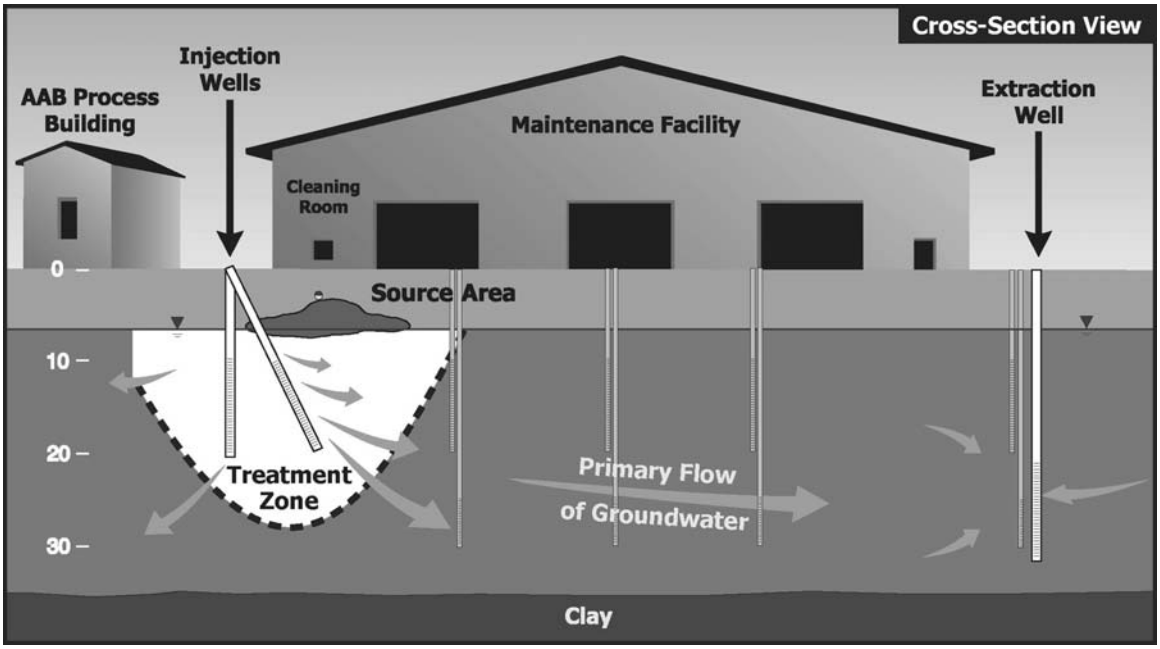

FIGURE 1 Building 719 conceptual model.

Second, the groundwater recirculation system maintains hydraulic control of affected groundwater. It also delivers substrate and nutrients to the microbes responsible for reductive dechlorination and recirculates dissolved phase contaminants into the treatment zone. Groundwater affected by the shallow source area under the upgradient side of the building is captured by extraction wells located on the downgradient sides of the building and reinjected through injection wells located near the source area.

PCE and TCE degradation products cis-1,2-DCE, vinyl chloride, and ethene that were detected prior to the installation of the AAB system indicated that reductive dechlorination of chlorinated solvents was occurring in localized zones within the source area. To accelerate contaminant degradation, organic carbon substrate (sodium lactate) and a metabolic nutrient (diammonium phosphate) are added to the recirculated groundwater prior to reinjection. The addition of substrate and nutrients has expanded the population of bacteria capable of complete reductive dechlorination of contaminants in the treatment zone.

Results from the first 4 years of system operations demonstrate the effectiveness of applying in situ AAB in conjunction with groundwater recirculation. Contaminant destruction rates consistently greater than 97 percent in the treatment zone have been presented in previous literature (Bloom, et al., 2005a). This paper focuses on the efforts made to control biofouling in the AAB system. Comparison of the three primary biofouling control strategies employed provides lessons learned for other AAB projects. In addition, two methods that have been effective at minimizing the negative effects of biofouling are identified.

BIOFOULING CONTROL METHODS

Selection of biofouling control methods for an AAB system must consider the important relationship between the biologically active treatment zone and the mechanics of the groundwater recirculation system. Optimizing the efficiency of the recirculation system,

as measured by flow rates, enhances capture of contaminants and can reduce remediation time by recirculating contaminants through the treatment zone at a faster rate. Maintaining recirculation efficiency relies primarily on controlling biofouling, mainly in the injection wells, but also in the extraction wells and system pipes. However, it is critical that biofouling control methods do not negatively affect the biological treatment zone, since contaminant degradation is the primary objective of the system. The two parts of the AAB system interface at the injection wells, making biofouling control at this location the most important and problematic.

Three primary strategies have been employed during the operation of the AAB system. The strategies, in chronological order of use, include:

Hydrogen Peroxide: From the beginning of system operations in February 2002 until approximately February 2004, hydrogen peroxide was used to restore permeability to injection wells after flow to the wells was substantially reduced due to biofouling in the well screen. This treatment was accompanied by vigorous physical redevelopment of the injection wells followed by purging of oxygenated water (which disrupts the anaerobic conditions) from the injection wells.

Anaerobic Biocide: From April 2004 through April 2005, an anaerobic biocide was applied to the injection wells when high pressures in the injection wells indicated biofouling. Although the biocide was used prior to April 2004, several initial applications were required to determine the most effective way to apply the biocide to the injection wells.

Substrate Injection Adjustment: From May 2005 through January 2006, biofouling was controlled primarily by limiting the presence of excess organic substrate in the groundwater recirculation components. This is accomplished by adjusting the rate of substrate injected so that just enough organic carbon is available in the treatment zone to ensure biological degradation of contaminants.

In addition to these three primary strategies, other attempts to control biofouling were made. Throughout the operation of the system, substrate and nutrients have been “pulsed” into the injection wells. Substrate and nutrients are added to injection wells at high concentrations for relatively short periods of time, as opposed to continuously injecting concentrations required for biological growth.

Pulsing results in substrate and nutrient concentrations too high for biological utilization in the injection wells and consequently limits biological activity. As injected materials move out into the formation, they are diluted and mixed, making them available for microbial growth outside of the injection well screens. After 16 months of system operations, in June 2003, the injection wells were converted to inject under pressure to push groundwater and amendments out of the well screens and into the formation. The injection wells, originally designed for gravity feed, were easily adapted to maintain pressures of less than 2.0 pounds per square inch (psi) at the well heads.

Controlling iron precipitation in the system components has also been required, although less frequently than for biofouling. Iron control strategies focus on limiting the growth of iron-related bacteria, which use dissolved iron for metabolic processes, as well as controlling iron precipitation. Therefore, iron control methods are mentioned here but they are not discussed in detail.

This paper focuses on the three primary biofouling control strategies identified above. More detailed discussion of all operation and maintenance strategies employed is included in previous literature Bloom, et al., 2005b).

OBSERVATIONS

The efficiency of the groundwater recirculation system is assessed by tracking the total flow of groundwater from the extraction wells over time (Figure 2a). Drops in the flow rate indicate system interruptions, which are most often related to biofouling. Higher flow rates indicate that the system is maintaining hydraulic control of contaminated groundwater and recirculating dissolved phase contaminants through the treatment zone as designed. Figures 2a, 2b, and 2c are each divided into three time periods defined by the primary biofouling control strategy used during each period, as labeled across the top of Figure 2a. Each of the parameters on the vertical axes (system flow, weekly substrate injection volume, and total organic carbon concentration) is an indicator of system efficiency.

Hydrogen Peroxide Treatments (February 2002 through February 2004). As shown in Figure 2a, the system flow rate decreased steadily during the first year of operation as the biological treatment zone around the injection wells expanded. System flow was restored by treating the injection wells with hydrogen peroxide in December 2002, yet system operations were hampered throughout 2003 due to continued fouling of the injection wells. System operations were repeatedly interrupted at the end of 2003, requiring multiple hydrogen peroxide treatments between November 2003 and March 2004 to fully restore system flow rates.

Recovery of flow rates after system shut-downs are the result of restored injection well permeability due to hydrogen peroxide treatments (first period of Figure 2a). Although hydrogen peroxide treatments were effective in restoring system flow, several limitations associated with the treatments were identified prior to and during the period:

1. Hydrogen peroxide treatments are expensive and labor-intensive. Significant volumes of oxygenated groundwater resulting from the addition of hydrogen peroxide must be purged from treated injection wells, treated, and/or disposed of. Dissolved oxygen is detrimental to the necessary anaerobic conditions in the treatment zone.
2. Handling a strong oxidizer like hydrogen peroxide creates health and safety concerns.
3. Hydrogen peroxide may cause precipitation of dissolved metals and off-gassing of degraded organic carbon, which reduces permeability in the aquifer.
4. Hydrogen peroxide treatments were less effective over time. Each treatment required a greater level of effort and resulted in shorter intervals between treatments.

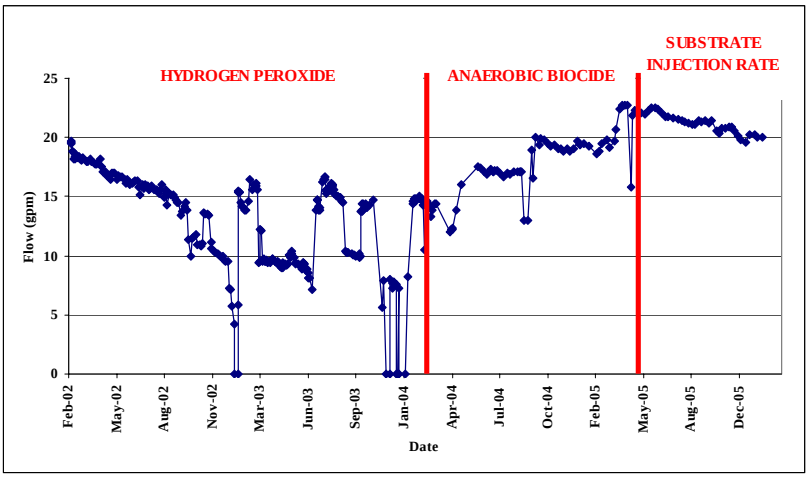

FIGURE 2a Total System Flow Rate.

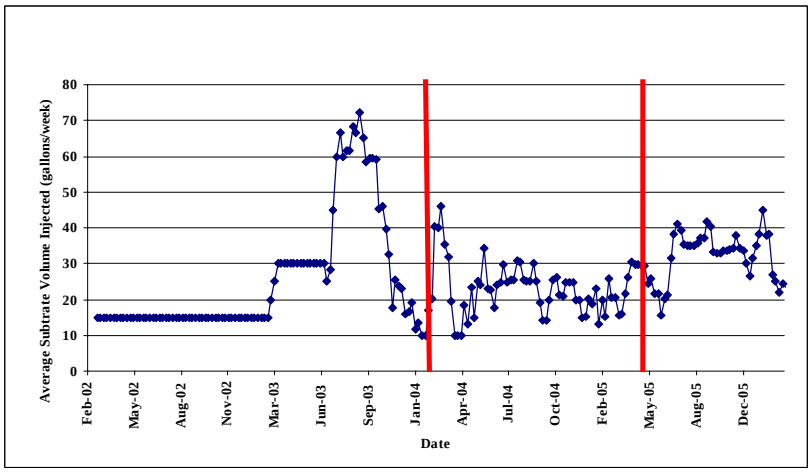

FIGURE 2b Weekly Substrate Injection Rate

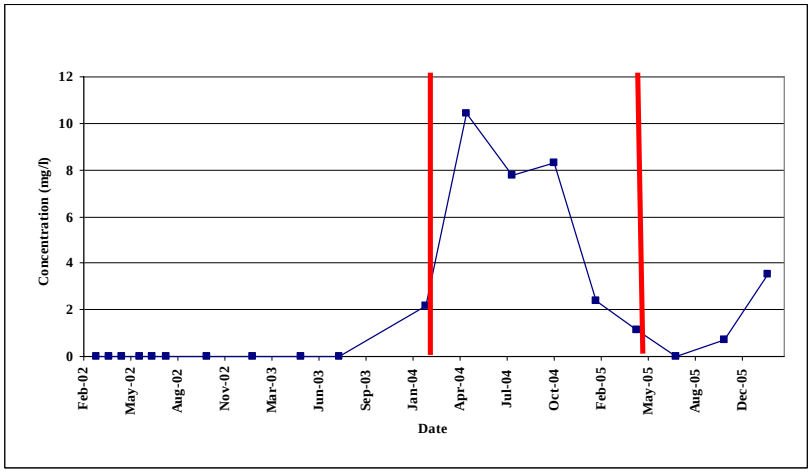

FIGURE 2c: Organic Carbon Concentrations in Recirculation System Components

Anaerobic Biocide (April 2004 through April 2005). To mitigate the limitations of hydrogen peroxide treatments, application of an anaerobic biocide to the injection wells began around February 2003. As mentioned above, an effective application protocol for the anaerobic biocide was not fully developed until April 2004. This is the second period in the charts in Figure 2. The need for an alternative to hydrogen peroxide to control biofouling intensified in July 2003 when the volume of substrate injected into the biological treatment zone (Figure 2b) was increased to maximize contaminant mass reduction during a period of high water table conditions. Between March 2003 and July 2003, injections of substrate into the system increased from 15 gallons per week to more than 60 gallons per week.

Although the higher substrate injection rate enhanced the desorption and degradation of source contaminants (Bloom, et al., 2005a), the resulting increase of organic carbon in the system was a primary factor contributing to biofouling. Figure 2c shows organic carbon concentrations in the pre-injection recirculated groundwater. Elevated total organic carbon (TOC) concentrations measured between February 2004 and May 2005 indicate that substrate was continuously available for biological growth within the system components.

Between February 2004 and May 2005, the anaerobic biocide was applied to injection wells as frequently as every 2 weeks. As shown in Figure 2a, during this time the system ran more effectively and without significant interruption, despite elevated TOC concentrations in the system components. This is attributed to anticipating biofouling in the injection wells and proactive application of the anaerobic biocide. The onset of biofouling could be predicted when pressure readings at the injection wells increased. When pressures approached 2.0 psi or greater in a majority of the injection wells, the anaerobic biocide was applied to the injection wells and the system was shut down for 12 to 48 hours. Applications prior to April 2004 demonstrated that contact time between the biocide and microbes for at least 12 hours was important for effective treatment. The system was then restarted and the biocide was allowed to disperse throughout the aquifer, where it was diluted and degraded to nontoxic byproducts. Monitoring of the biocide's active ingredient in the groundwater demonstrated that the biocide does not persist in the aquifer beyond the injection wells.

Increasing system flow rates during the application of the biocide demonstrate its effectiveness for controlling biofouling (Figure 2a). In addition, groundwater monitoring showed that the biocide did not adversely affect the geochemical conditions in the anaerobic treatment zone, as was the concern with hydrogen peroxide. However, there were other concerns associated with the use of the biocide.

1. Regulatory approval and thorough demonstration that the biocide would not impact any surface water bodies was required prior to use in the system.
2. Although data indicate that the biocide did not negatively affect the biological treatment zone, the biocide does kill microbes involved with contaminant degradation if not applied appropriately.

Substrate Injection Adjustment (May 2005 through January 2006). As the significance of the relationship between high TOC and biofouling became more apparent, operation and maintenance (O&M) efforts were directed toward determining an ideal substrate injection rate that balanced contaminant degradation efficiency in the treatment

zone while minimizing biological growth in the system components. This is the third time period indicated in Figure 2. As the water table receded slightly in September 2003, the substrate injection rate was reduced (Figure 2b). As a result, TOC concentrations declined between February 2004 and May 2005 (Figure 2c). Decreasing TOC concentrations correspond to increasing system flow rates greater than 20 gallons per minute (gpm) observed through January 2006 (Figure 2a). Hydrogen peroxide and anaerobic biocide treatments were not required during the last time period (May 2005 through January 2006), emphasizing the importance of limiting the availability of organic carbon in the system components.

The substrate injection rate was increased in July 2005 after groundwater data collected in April 2005 indicated that the anaerobic conditions in the treatment zone were diminishing due to insufficient TOC. Although subsequent groundwater data demonstrated that the conditions in the treatment zone were restored by the increased substrate injection rate, Figure 2c shows the recurrence of TOC in the system components. Further analysis of the system operations and the results of substrate injection rate adjustments are required to determine if an ideal substrate injection rate can be achieved.

CONCLUSIONS

Operation of the in situ AAB system at DAFB for over 4 years has demonstrated that biofouling issues often associated with this groundwater remediation technology can be reasonably mitigated with appropriate knowledge and understanding of both the technology in general and project-specific characteristics. Concerns related to biofouling should not disqualify the selection of in situ AAB for remedial actions, but should be considered when developing an effective strategy that is proactive and responsive to changes in physical and geochemical conditions. Specific observations discussed in this paper include the following:

1. Costs and level-of-effort can be minimized by adjusting the substrate injection rate to maintain conditions favorable for reductive dechlorination in the treatment zone while simultaneously limiting available organic carbon in system components. This strategy also minimizes the need for chemical treatments to address biofouling in injection wells, which may negatively affect microbes or geochemical conditions required for contaminant destruction in the treatment zone.
2. An ideal substrate injection rate may be difficult to determine and maintain due to fluctuating groundwater conditions and changes in substrate utilization by microbes. However, finding the ideal rate is likely to minimize the need for less preferable chemical treatments.
3. An anaerobic biocide can effectively control biofouling in the injection wells if an ideal injection rate cannot be maintained. Prior regulatory approval should be obtained early in the planning process.
4. Hydrogen peroxide treatment is effective in restoring permeability to biofouled injection wells. This strategy is not proactive, however, and is expensive and labor-intensive. Hydrogen peroxide should be considered an option of last resort due to its manifold limitations.

5. Aggressive chemical treatments (including hydrogen peroxide and biocide) can be applied to in situ AAB systems without negatively affecting the biological treatment of contaminants. Possible effects of these treatments need to be identified and monitored whenever chemical treatments are used.

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