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Research article

Design and performance of subgrade biogeochemical reactors

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ABSTRACT

Subgrade biogeochemical reactors (SBGRs), also commonly referred to as in situ bioreactors, are a unique technology for treatment of contaminant source areas and groundwater plume hot spots. SBGRs have most commonly been configured for enhanced reductive dechlorination (ERD) applications for chlorinated solvent treatment. However, they have also been designed for other contaminant classes using alternative treatment media. The SBGR technology typically consists of removal of contaminated soil via excavation or large-diameter augers, and backfill of the soil void with gravel and treatment amendments tailored to the target contaminant(s). In most cases SBGRs include installation of infiltration piping and a low-flow pumping system (typically solar-powered) to recirculate contaminated groundwater through the SBGR for treatment. SBGRs have been constructed in multiple configurations, including designs capable of meeting limited access restrictions at heavily industrialized sites, and at sites with restrictions on surface disturbance due to sensitive species or habitat issues.

Typical performance results for ERD applications include 85 to 90 percent total molar reduction of chlorinated volatile organic compounds (CVOCs) near the SBGR and rapid clean-up of adjacent dissolved contaminant source areas. Based on a review of the literature and CH2M's field-scale results from over a dozen SBGRs with a least one year of performance data, important site-specific design considerations include: 1) hydraulic residence time should be long enough for sufficient treatment but not too long to create depressed pH and stagnant conditions (e.g., typically between 10 and 60 days), 2) reactor material should balance appropriate organic mulch as optimal bacterial growth media along with other organic additives that provide bioavailable organic carbon, 3) a variety of native bacteria are important to the treatment process, and 4) biologically mediated generation of iron sulfides along with addition of iron pyrite sands as an abiotic polishing step within the reactor has been observed to be an efficient treatment train for chlorinated solvent sites.

1. Introduction

This paper discusses the background, design considerations, advantages, limitations, and performance of SBGRs (Gamlin et al., 2016). Bioreactors have been used in the remediation industry for treatment of CVOCs since the early 2000's (Air Force Center for Engineering and the Environment [AFCEE], 2008; Downey et al., 2005; Environmental Strategic Technology Certification Program [ESTCP], 2002). The class of bioreactors discussed in this paper were first implemented in 2008 (CH2M, 2011a), and are referred to as SBGRs because they incorporate both biological and biogeochemical degradation processes.

2. Background

This section provides a historical overview of the SBGR technology and presents the typical applications, advantages, and limitations.

2.1. Historical overview

The use of in situ biological reactors for treating chlorinated solvent source areas was described by ESTCP (2002). In a follow up ESTCP project, field testing of a groundwater recirculation

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bioreactor was initiated in 2003 at Site LF-3 at Altus Air Force Base (AFB), Oklahoma. Results from this testing demonstrated the ability of a mulch and gravel filled bioreactor to create the anaerobic conditions necessary for reducing CVOCs, such as trichloroethene (TCE), *cis*-1,2-dichloroethene (DCE) and vinyl chloride (VC) both inside and outside of the bioreactor (Downey et al., 2005). Parallel research by the United States Environmental Protection Agency (USEPA) Robert Kerr Laboratory discovered that the combination of wood mulch and cotton gin trash, along with high natural sulfate and iron levels, were producing iron sulfide particles inside a permeable biowall also being tested at Altus AFB (Shen and Wilson, 2007). This reactive iron sulfide was found to promote abiotic reduction of TCE to acetylene and carbon dioxide (He et al., 2008).

The convergence of these research findings led to the construction of the first SBGR in late 2008, which was engineered to include biological and abiotic biogeochemical transformation. This SBGR was installed as a technology demonstration project to replace a dual phase extraction system that had operated for over 10 years at Site DP039 at Travis AFB, California. The SBGR included a combination of gravel, mulch, and vegetable oil to promote biological reduction, as well as iron pyrite sands to promote abiotic CVOC reductions within the SBGR. As discussed in Section 4.1, this SBGR was installed in an 8 mg per liter (mg/L) TCE source area and after the first 1.5 years of operation this SBGR achieved a 99 percent total molar reduction of dissolved TCE, DCE, and VC in the targeted source area (CH2M, 2011a), and has since achieved concentrations below the USEPA maximum contaminant level (MCL) in the aquifer surrounding the SBGR (CH2M, 2016a). Since 2008, over a dozen more SBGRs have been installed in a number of different geographies and configurations (see Section 4).

2.2. Typical applications

This section describes some of the typical applications of SBGRs.

2.2.1. Source area treatment

The most common application of SBGRs has been in chlorinated solvent source areas, particularly smaller sources associated with underground storage tanks, oil-water separators, and small chemical pits. Other contaminant source areas associated with releases of fuels, explosives, pesticides, metals, etc. can also be treated by SBGRs. Well characterized and defined sources can be excavated or partially excavated for SBGR construction. The SBGR then treats soil and groundwater contamination near the SBGR.

2.2.2. Persistent groundwater hot spots

SBGRs can be installed over the top of persistent groundwater hot spots where a source is suspected. An extraction well can be screened in the most contaminated aquifer interval and this contaminated groundwater is then pumped and infiltrated through the SBGR for treatment. Dissolved treatment amendments that are flushed out of the SBGR can promote biodegradation, or in some cases abiotic treatment, providing additional in situ treatment of residual contaminants in the surrounding soil and aquifer.

2.2.3. Replacement of source area pump-and-treat or other ex-situ systems

The limitations of groundwater extraction systems at remediating source areas are well documented, particularly in heterogeneous formations (Nyer, 1993; USEPA, 1990, 1997). Pumping systems can result in limited mass removal due the slow processes of contaminant diffusion out of the aquifer matrix. Extracted groundwater must also be treated with other technologies, such as activated carbon, thus creating extra cost, extra energy use, a separate waste stream, and an increased life-cycle environmental footprint compared to that of the SBGR, which treats the groundwater in situ.

SBGRs have been used to replace existing ex-situ treatment systems for more effective treatment while reducing operations and maintenance (O&M) requirements. The Site CG040 SBGR at Tinker AFB, Oklahoma, was installed to optimize an existing pump-and-treat system. This allowed for an air stripper treatment unit to be shut down while accelerating treatment by inducing recirculation of ERD amendments through the aquifer (see Section 4.7). This optimized system supported a 99 percent total molar reduction of dissolved source area CVOCs, which had an initial TCE concentration of 0.72 mg/L prior to SBGR startup. Another example is the Site SS016 SBGR at Travis AFB, California, which replaced a dual-phase extraction system that was used to treat a soil and groundwater source area. This SBGR included excavation of low-permeability soils and bedrock containing TCE. A 99 percent reduction in dissolved total molar CVOC levels was rapidly achieved in the source area, which had an initial TCE concentration of 182 mg/L during startup of the SBGR (see Section 4.2). The SBGR expedited treatment while reducing projected lifetime O&M costs by approximately $4.6 million and greenhouse gas emissions by 936 tons of carbon dioxide associated with operating the dual-phase extraction system's thermal oxidizer.

2.2.4. Polishing following in situ treatment applications

In situ chemical oxidation can be effective at reducing high levels of CVOCs in permeable soils; however, the oxidation process in many cases has a relatively short reaction time. As a result, many oxidant injections fail to contact all of the contaminants, and incomplete treatment can result in contaminant rebound. At these sites an SBGR can be installed in the residual source area to provide an ongoing source of treatment for soils and groundwater. This approach can also be relevant for polishing of other in situ approaches, such as in situ chemical reduction or air sparging applications.

2.2.5. Operational life-cycle

The life-span of the organic carbon within the reactor is dependent on several site-specific factors and the type of mulch used. Based on nine SBGRs that have operated for three years or more, only two have required emulsified vegetable oil (EVO) injection to replenish dissolved organic carbon concentrations. One SBGR used fresh mulch instead of composted mulch and required recharge after two years. The other SBGR used composted mulch, but was recharged after four years because total organic carbon concentrations dropped below 10 mg/L.

2.3. Advantages of subgrade biogeochemical reactors

A primary advantage of the SBGR technology is that once contaminated soil is removed and groundwater is treated within the reactor, the treated groundwater is dispersed to the aquifer, allowing for cycling and dispersal of lower concentration water containing in situ treatment amendments throughout the aquifer. Recirculation of this water throughout the treatment zone creates a concentration gradient that can induce diffusion of contaminants residing in low permeability portions of the aquifer into the groundwater advection pathways. SBGRs also circulate treatment amendments immediately beneath the infiltration system where groundwater flows down through the vadose zone, as well as the variably saturated zone beneath and adjacent to the SBGR, which can allow for treatment of contamination typically inaccessible to direct substrate injection approaches. SBGRs limit O&M issues typically associated with injection well fouling and therefore can be more successful than recirculation approaches that use injection wells.