Enhanced In Situ Aerobic Biodegradation of BTEX Using Diffusive Oxygen Emitters

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Introduction

Complete aerobic biodegradation of gasoline plumes near source is often not possible because the oxygen demand imposed (i.e. plume concentrations) exceeds the solubility of oxygen. Since gasoline constituents are known to readily biodegrade naturally, it may only be necessary to treat a fraction of contaminant mass flux. However, to implement what has been called enhanced in situ aerobic bioremediation, the challenge still remains to deliver as much oxygen as possible for a sustained period in a cost-effective manner.

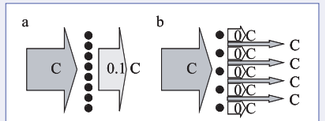

Figure 1. Uniform partial treatment (a) and pin stripe treatment (b), both achieving the same overall mass flux reduction. Fewer wells may be required to achieve treatment shown in (b).

Often, treatment systems must be installed close to the NAPL source, which results in a very high contaminant loading. This poses an unrealistic performance demand, and a more appropriate aim of remediation may be strategic mass flux reduction. Diffusive oxygen emitters (Wilson and Mackay, 2002) can provide the desired oxygen release performance, and if deployed appropriately can result in a significant fraction of total contaminant mass flux reduction. Discontinuous well arrays are one deployment option that can achieve two goals: overall mass flux reduction and an increase in plume surface area. By treating strips of a plume ("pin striping"), more internal plume area is exposed to background electron acceptors, thereby enhancing natural attenuation (Figure 1).

Field Experiment

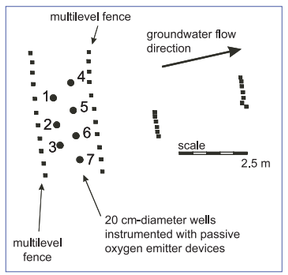

Figure 2. Treatment well array and ML fence configuration

A seven 10" diameter well array (Figure 2) was installed across a portion of a gasoline plume migrating through an unconsolidated, medium sand aquifer. High resolution multilevel point sampler fences (~22 cm horizontal x 15 cm vertical) were installed up and downgradient of the well array and snapshot sampled on five occasions to allow estimation of mass flux flowing into and out of the treatment array. Into each well was installed an oxygen emitter consisted of a length of LDPE tubing coiled around a PVC frame (Figure 3). The tubing was connected to a pressurized cylinder of 95% oxygen/5% SF6, the latter serving as a tracer of oxygen release and transport. Once pressurized, the imposed concentration gradient drives oxygen across the tubing wall into groundwater flowing through the well.

Emitters 4-7 were operated at 60 psi for the first three months and all emitters were pressurized to 90 psi for the final three months (15 mg/L and 25 mg/L DO respectively). Since total BTEX concentrations influent to the treatment array were in excess of 100 mg/L in places (and spatially variable), it was not expected that complete treatment would be achieved. The aim of this experiment was to estimate BTEX mass flux up and downgradient of the well array, and compare apparent mass flux reduction to that expected solely as a result of oxygen delivery.

Figure 3. Photo of diffusive oxygen emitter

Performance of Emitter Well Array

Dissolved oxygen concentrations in the emitter wells approached that predicted (Figure 4), but no increase in DO was noted at the downgradient ML fence. As expected concentration and distribution of SF6 in the downgradient fence demonstrate that water continued to flow through the array during the experiment (no biofouling or plume bypass). Given a groundwater velocity of 9 cm/day, we estimate that approximately 7.5 Kg of oxygen was delivered during the test.

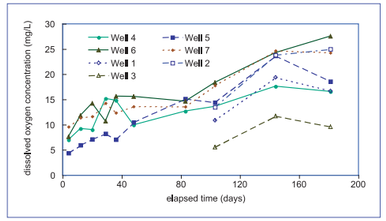

Figure 4. Dissolved oxygen concentrations in the emitter wells during the experiment. Only emitters 4-7 were pressured initially; all emitters were operated. Poor performance of emitter well 3 was attributed to a pinch in the gas supply tubing to that well, which compromised the imposed diffusive gradient.

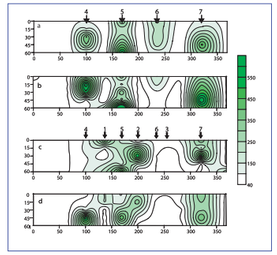

Figure 5. SF6 concentrations in the downgradient ML fence for snapshots 2-5. Problem associated with gas supply noted in Figure 4 is evident here in snapshot 4 and 5.

Influent and Effluent BTEX Concentrations

Visual comparison of Fence 1 and Fence 2 benzene concentrations before startup of oxygen release (Figure 6) and after all emitters were brought on line (Figure 7) indicate causal relationship between oxygen release and benzene decrease. Pure gasoline NAPL was sampled from MLs 9-11 (upgradient of emitter wells 3 and 7), indicating that mobile NAPL was moving into the treatment array during the experiment. No NAPL was sampled in the downgradient fence, but some BTEX was undoubtedly lost to volatilisation

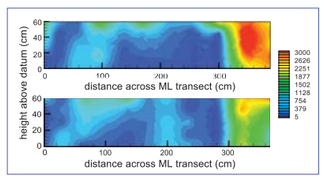

Figure 6. Concentration distribution of benzene in the ML fence upgradient (a) and downgradient (b) of the emitter array before the start of oxygen release.

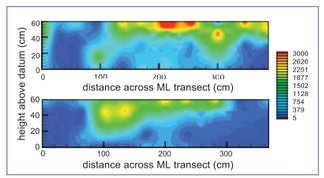

Figure 7. Concentration distribution of benzene in the ML fence upgradient (a) and downgradient (b) of the emitter array when all wells were releasing oxygen.

Assessment of Mass Flux and Flux Reduction

The Thiessen polygon method was used to estimate mass flux across ML fence 1 and 2. MLs 4-10 from fence 1 and MLs 14-21 from fence 2 were used to estimate flux, because no enhanced treatment of mass migrating along the line between MLs 1-3 and MLs 12-13 or ML11 and ML22 was expected. Figure 8 shows the estimated influent and effluent mass flux for the 5 snapshots, and the percent difference between the two. Note that there is a 16% drop in mass flux for snapshot 1 (before start of oxygen release): this is a combination of natural attenuation and volatile losses. Enhanced mass flux reduction peaks at 55% over and above NA at snapshot 4, when all emitters were operating. There is only modest enhancement (~15% above NA) in the first 90 days when only 4 emitters were operated. Data not presented suggest that the degradation of aromatics was preferred over aliphatics. If aliphatics were preferred, they would impose an oxygen demand that would compromise BTEX treatment. Order of expression of oxygen demand should be assessed for any in situ aerobic remediation application (including non-target organics, non-plume organics and reduced metals).

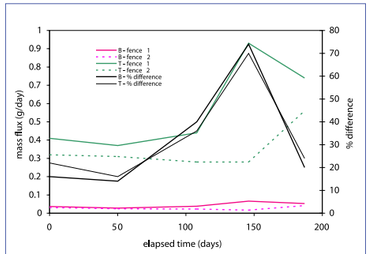

Figure 8. Mass flux in fences 1 and 2 for each of the five snapshot events, and the percent difference between fence 1 and fence 2 flux - an indication of treatment performance.

Summary

Passive diffusive emitters are capable of steady oxygen release over a prolonged period. Deployment in arrays of wells allows for strategic mass flux reduction, the nature of which is a function of well spacing. Where it is possible to rely on natural attenuation for a portion of treatment, it may be possible to relax well spacing such that the combination of engineered mass flux reduction and natural attenuation results in concentrations that are within tolerance at some compliance point. In this study, an array designed to achieve 100% hydraulic capture of a high concentration gasoline constituent plume (far in excess of maximum DO solubility) achieved a 30% enhancement of natural attenuation of BTEX mass flux (70% overall reduction). No biological or iron fouling of the emitter wells was noted in this short field trial: wells were slug tested before and after the test (similar hydraulic conductivity), and the continued transport of SF6 from the emitter wells to fence 2 confirm continued groundwater flow.

Acknowledgements

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References

Wilson RD and Mackay DM. 2002. Diffusive oxygen emitters for enhancement of aerobic in situ treatment. GWMR Spring 2002, pp 88-98.