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Using Bioreactors for Localized Cleanup of Petroleum Contaminated Groundwater:
Soo Yard, Minneapolis, Minnesota

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Reclamation and redevelopment of contaminated industrial sites in central cities is viewed by many as a primary antidote to sprawling metropolitan areas. Redevelopment of highly valued urban lands present the opportunity to strengthen communities through job and housing creation, bridging of spatial gaps left by abandoned industry and the removal of potential hazards to human health. The Twin Cities of Minneapolis and St. Paul have more than two thousand acres of land identified as potential "brownfields" sites that have been tied up in litigation for decades (Simons, 1998). For urban sites, rapid remediation is a priority, as many of these areas are located on highly valued real estate. Until recently, excavating and disposing of contaminated soils has been the standard mode of cleanup. While this method can be expensive, an even greater threat is that property owners remain liable for the disposed fill for the remainder of its existence. For this reason, *in situ* remediation, when possible, offers the potential for permanent closure on the issue of site contamination, both legally and ecologically. This paper will examine the use of a bioreactor to clean up localized petroleum based pollutants, focusing on the reclamation of the Soo Line Railyard in South Minneapolis as a case study.

Brownfields and Redevelopment of Urban Centers

In the United States, there are more than 400,000 listed contaminated sites (Simons, 1998). Of these, 1,318 are listed as top priority Superfund sites and another 11,298 are designated CERCLIS sites, or second priority Superfund candidates. In 31 of the U.S. largest cities, estimates put the number of contaminated brownfields above 75,000 locations whose reclamation and redevelopment are contingent upon their reduced toxicity in the landscape. In Minneapolis and St. Paul, Minnesota, contaminated sites are listed as 1,030 and 210 respectively, not including a number of large Superfund and other sites in the adjacent suburban areas (Simons, 1998). This land often sits in locations where development of needed jobs and housing is limited by the threat of health concerns as well as the legal liability of future development.

While the number of total contaminated sites spread throughout the nation is daunting, new approaches to cleanup can offer some hope, particularly when cleanup technologies address the most pervasive of issues. Frank Fekete (1994) estimates that there are some 375,000 leaking gasoline storage tanks across the United States. Clearly, limiting current leakage is essential. However, dealing with those sites already contaminated is key to reclaming the landscape for either ecological restoration or cultural development. Prior to 1990, standard mode of operation for cleanup tended to rely on excavation and disposal. A 1985 U.S. Congressional Budget Office Report stated that "68 percent of the nation’s toxic wastes are still disposed of in the land by deep-injection, surface impoundments, pits, ponds and landfills...22 percent of the wastes is discharged directly into sewers, rivers, and streams, whereas 5 percent is incinerated or burned and only 5 percent is recycled, reused or processed to reduce toxicity (Fekete, 1994)." By 1991, the EPA and state governments were beginning to encourage the use of alternatives to landfilling of wastes. In a 1991 EPA report on 535 Records of Decisions for site cleanup projects, only 34 percent were containment and disposal operations, where the remainder of reclamations were beginning to run the gamut from solidification, incineration, soil washing, and solvent extraction to in-situ vitrification, bioremediation and soil vapor extraction (Fekete, 1994). Embracing new technologies in a difficult environmental and legal atmosphere had been the challenge, however, the EPA has been increasingly shifting the power of approval back to the states in an effort to encourage cleanup, rather than stagnation of contaminated lands. Indeed, in 1995, the State of Minnesota passed the Contaminated Sites Cleanup Program, designating $7.8 million for cleanup of contaminated sites (Bartsch and Collaton, 1997), recognizing the shifting control from EPA to the Minnesota Pollution Control Agency (MPCA).

Background on the Soo Line Railyard

The Soo Line Railyard (SLR) is located in a mixed residential, industrial area bounded by Hiawatha and Minnehaha Avenues between 26th and 28th Streets in South Minneapolis. Historically, the 40-acre site had been used by the Milwaukee Road regional rail company for a variety of operations relating to train switching yard activities. Due to the nature of reclamation of contaminated landscapes, site assessment requires in depth analysis of both the geologic and hydrologic soils makeup as well as cultural and historical uses on any given site in order to both understand the nature and magnitude of contaminants. Testing procedure as well as the ability of the natural landscape to respond favorably to remediation techniques will play a significant role in the success or failure to adequately address contamination in a site responsive manner.

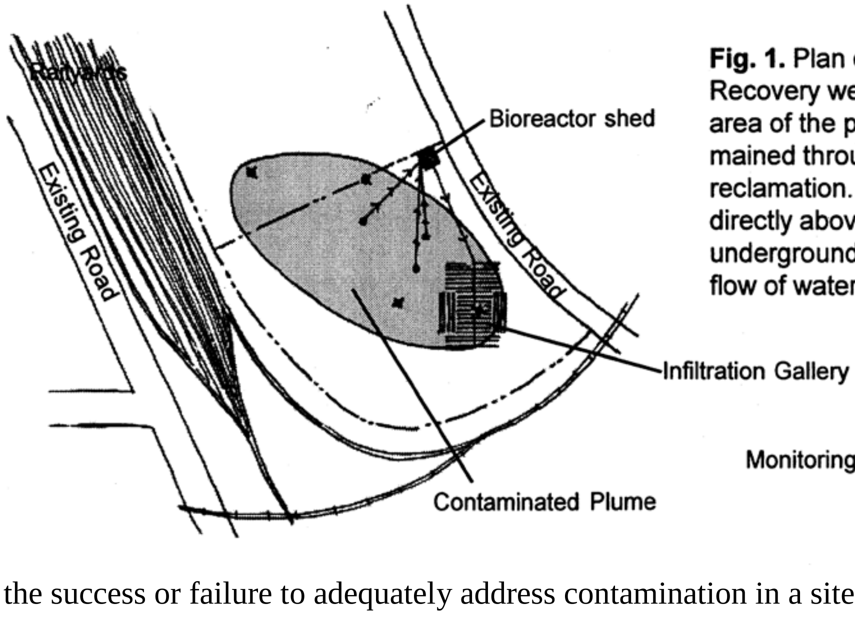

Fig. 1. Plan of the southern zone of SLR site. Recovery wells were placed central in the area of the plume. Monitoring wells remained throughout the process to track reclamation. Infiltration gallery is located directly above the area of the removed underground storage tank. Arrows indicate flow of water.

The geologic history of the SLR site played an important role in the remediation technique chosen. Located on a middle terrace of the Glacial River Warren, the surficial geology of the site is composed of approximately 20-30 feet (6-9 meters) of primarily well drained, sandy material underlain by 10-30 feet (3-6 meters) of glacial till. The Bedrock of Decorah Shale and Platteville

Limestone slopes slightly to the northwest at roughly 40-50 feet (12-15 meters) below the surface. Depth to water ranged from 20 feet (6 meters) at the southern portion of the site to 25 feet (7.6 meters) on the north end. Both groundwater velocity as well as hydraulic conductivity were rated as relatively high for areas of glacial till.

Following nearly a century of degradation as an industrial service area, an upper surface of fill, composed of mixed bituminous, concrete, sand and gravel extended down to seven feet over much of the site. The major on site-cultural uses included transfer docks, automobile storage, maintenance facilities as well as siting of underground fuel storage tanks. Due to the range of industrial activities on site, pollutant loads in the various sectors ranged dramatically from heavy metals and heavy fuels located in the northern portion, to minimal amounts of pollutants in the eastern areas (car storage), to the gasoline related storage tank pollution in the southern portion.

Between 1984 and 1986, the Minneapolis Community Development Agency (MCDA) along with the Milwaukee Road and Soo Line Rail Companies began environmental assessments to move toward the redevelopment of parcels and full transfer to MCDA control. Following initial assessments, the MCDA, as the primary development arm of the City of Minneapolis, took control of the site with the intention of job development.

Testing Procedure and Identification of the Southern Zone

Following initial site analysis, the MCDA established a plan to divide the site based on the extent and nature of pollutants. The eastern portion (a former automobile marshalling yard) was deemed sufficiently clean by the MPCA to sell and develop immediately. The problem areas remained in the northern portion where a 3 ½ foot (1 meter) layer of compounds related to coal tar derivatives as high as 5.6 ppm were reported in initial testing. In the southern region, an area surrounding an underground gas storage tank showed high levels of gasoline related compounds in both the soil and groundwater. Due to the distinct remediation possibilities of these two types of pollutants, the MCDA along with Engineering firm Braun Intertec began intensive testing throughout the site with an emphsis on the northern and southern portions.

In spring, 1988, detailed subsurface investigations were performed with 71 soil borings at a center spacing of 200 feet (61 meters) with special areas of concern receiving greater coverage. Six groundwater monitoring wells were installed which provided ongoing monitoring capabilities. This site analysis saturation allowed the definition of plumes of contamination to be designated, and where fuel oil and other hydrocarbons were identified, soil and groundwater analysis were performed.

Analysis of both soil and groundwater indicated Total Hydrocarbons (THC) as gasoline at levels of 220 ppm at the 25 foot (7.5 meters) depth and 53 ppm at 10 feet (3 meters) immediately adjacent to the area of a former Underground Gasoline Storage Tank (UST). Other monitoring wells indicated that a plume of contaminated soil and groundwater extended north west over 16,500 square feet (5030 square meters), containing a soil volume of approximately 13,500 cubic feet (4100 cubic meters). The primary concern with the contamination on this site was with the gasoline related compounds found at levels more than 2500 times the maximum concentration allowed for by the Minnesota Department of Health. Compounds of concern found in excessive levels in groundwater tests included acetone, benzene, ethyl benzene, methyl ethyl ketone, tetrahydrofuran, toluene and xylene (this complex is commonly referred to as BTEX).

Soils tests at a 10 foot depth indicated levels of THCs well above recommended allowances as well. Sampling for metals showed levels above what would be permitted for residential development. Of particular concern were lead levels at a concentration of 200 ppm, or twice the allowable level of 100ppm for residential development (MPCA, 1998). Because the MCDA had committed to developing the site for light industrial usage, bituminous parking lot as well as concrete building footprints were permitted to act as "caps" for what were considered moderately problematic levels of lead and other heavy metals.

The MPCA and National Pollutant Discharge Elimination Standards (NPDES) set limits for the release of pollutants back into wastewater sewage systems which the MCDA set as goals to meet or exceed for each of the components of THC present in both groundwater and soils. The MCDA set limits for each of the THC compounds after cleanup to 100 less than the Recommended allowable limits guidelines for water and soil reductions to 50 ppm of THC for soils.

Alternative Treatments Considered by MDCA for Treatment of the Southern Zone

The MCDA contracted Braun enterprises to provide a list of alternatives for remediation of each of the contaminated zones in the Soo Yard. The remainder of this paper will focus on the Southern Zone, where the use of a bioreactor was eventually chosen. The alternatives for remediation of the site included both *in-situ* as well as *ex-situ* remediation techniques for both soil and groundwater cleanup. Although time was a factor in the cleanup of the site, Larry Heinz, chief engineer at the MCDA points out that at the outset of this project, there were no buyers for the land lined up. The MCDA set up a two year outside time limit for remediation of the southern zone, which allowed Braun and the agency time to explore a range of technological solutions. The following forms of remediation were explored as alternatives:

In situ Volatilization (ISV) - This is a system of mechanically venting air through contaminated soil in order to mobilize VOCs trapped in an anaerobic underground situation. The Soo site was an ideal candidate for this remediation technique due to highly permeable soils. The effectiveness of this technique is limited by the rate of VOCs venting into the atmosphere, which in a highly contaminated site requires air filtration and thus the continuing liability for the byproduct of contaminated filters in landfills.

In Situ Biodegradation **-** This technique treats both groundwater and soil through the stimulation of microbes already present on site through the supply of oxygen, phosphorous and nitrogen in an aqueous phase. The technology allows for a closed loop system, whereby groundwater is collected through wells at the lower end of a plume of contaminants, treated, and discharged again in the upper reaches of the same plume. Because the procedure flushes oxygen and nutrient rich water through a contaminated plume, it is effective in the cleanup of both groundwater and soils.

Ex Situ Land Treatment **-** This soil treatment involves the excavation of all contaminated soils and spreading them thinly over another area to allow for biodegradation and volatilization to occur. The limititation of this technology is related both to the uncertainty of time for remediation as well as the requirement of a minimum of 25 acres for landfarming of the soil.

Thermal Treatment **-** This technology also requires excavation of soils for treatment. Thermal treatment relies upon removing soils and placing them into a treatment unit where air flow, combustible temperatures and agitation release VOCs to a filtration system. This method has drawbacks relating to the creation of various by-products in the capture of THCs as well as heightening the leaching of heavy metals, particularly lead. As an already expensive procedure, thermal treatment also requires the ongoing liability of both on and off site immobilized lead as well as the continuing responsibility for carbon filters sent to landfills.

Air Stripping **-** This method of groundwater treatment involves pumping contaminated water to the top of a constructed tower filled with a material of high surface area and large void spaces. Blown air from beneath allows VOCs with an affinity for a gaseous stage to discharge from the groundwater. This method addresses only the groundwater and may require the use of a carbon filter and thus ongoing liability for contaminant.

Carbon Adsorption **-** Essentially a filtering system, carbon adsorption involves pumping contaminated groundwater through a series of reactors packed with activated carbon. The method is effective for compounds with low polarity, but the presence of compounds such as oil and grease cause clogging of the carbon reactor system. This method does not destroy the pollutants and requires removal of contaminants to a landfill.

Above Ground Bioreactor and Infiltration Gallery for In-Situ Cleanup

Since the MPCA and MCDA deemed the levels of heavy metals in the southern zone of the SLR site to be acceptable under the development of light industry, technology to address the VOCs specifically were considered appropriate. The above ground bioreactor was chosen for the southern zone of the SLR site based on the perceive benefit of low risk of continuing liability and the permanence of treatment. Since the bioreactor method creates as by product only oxygen, added nutrients, carbon dioxide and additional indigenous bacteria, it offers the possibility of full treatment of VOCs on site. The bioreactor designed for the SLR site combined in-situ soil treatment with ex-situ groundwater treatment. The flushing process aerated and enriched both groundwater and soils in a closed loop system based on the extent of the plume of gasoline contaminated soils and groundwater.

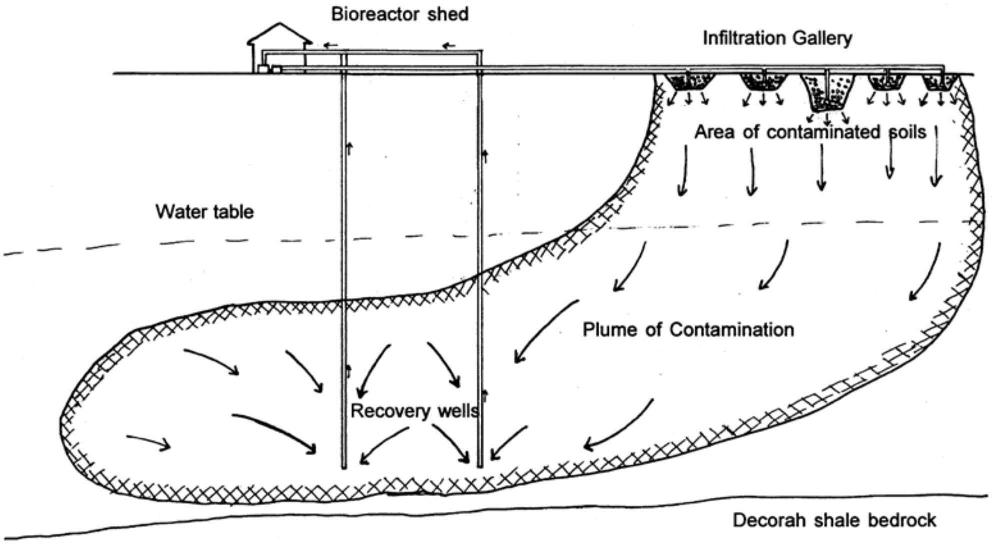

Fig. 2 Section diagram of contaminated SLR site. Infiltration gallery treats contaminated soils through flushing before water reenters contaminated groundwater plume.

Bioreactor technology is referred to as *enhanced biorestoration* (Boulding,1995). The process relies largely on aerobic degradation, where oxygen is added to the contaminated site to serve as an electron acceptor, converted to water and can by used by microorganisms. The addition of oxygen allows microorganisms dependent upon on aerobic conditions to out compete anaerobic microrganisms. Gasoline, the primary toxin on the SLA site, is easily biodegraded in aerobic conditions, (Boulding, 1995) but not readily biodegradable in the absence of oxygen. The keys to successful cleanup are related to the porosity of soils on site, hydrologic conditions, the ability to identify the upper and lower end of a contaminant plume, and the presence of local microorganisms to detoxify pollutants.

The SLR site contamination was comprised of 16,500 square feet (5030 square meters) of vadose layer soil (the subsurface area above the water table) contaminated in the area of monitoring well #103, directly adjacent to the removed leaking storage tank. Beyond this area, a deeper oval plume of polluted groundwater extended over much of the site over 45 deep (13.5 meters) Decorah shale bedrock sloping downward to the north west. This situation allowed for enhanced biorestoration to work on two levels. First an infiltration gallery approximately140' X 210' (43 X 64 meters) was constructed over the area of contaminated soil at the topographical upper end of the underground plume. Second, a series of three pumping wells were constructed at the lower level of the contaminated plume, drawing water from near the surface of the bedrock up into a small shed housing the bioreactor device. The *PetroClean* bioreactor designed by ESE Biosciences, Inc consisted of a phase separator to remove accumulated solids, preventing buildup the bioreactor. This general framework allowed for a closed loop of groundwater flow and contaminant biodegradation.

Bioreactor design is based on bringing together an electron acceptor (nitrogen or oxygen), microbial biomass and nutrients with organic compounds as a source of energy. In this case, the organic compounds in question are the toxic hydrocarbons associated with gasoline. The bioreactors used at the SLR site were of the submerged fixed-film type where toxins are diluted, aerated and flushed through a series of baffles where they came into contact with aerobic bacteria. Initial startup filled the tanks with polluted waters and allowed bacterial populations to establish and stabilize. The process of degradation is rapid. Limits of pH and ammonia nitrogen were established according to maximization of biodegradation. After the first phase of biological decontamination, the bioreactors at the SLR site allowed for an influent and effluent rate of roughly 10 gallons per minute. ESE determined an appropriate ratio of nitrogen to phosphorous to promote microbial activity, then maximized the concentrations to the allowable effluent limits. The intent of the maximization of levels in the effluent was to inoculate the contaminated soils in the gallery area with oxygenated, nutrient and microbial rich remediated water. Following discharge into the gallery, reactor additions of oxygen and nitrogen facilitated the continued biodegradation in the subsurface of the site, where indigenous microbial activity was enhanced through in-situ aeration of soils and groundwater. The flow through this zone then traveled through the contaminated plume of groundwater where uptake occurred at the three recovery wells located at the downstream end of the plume.

This "closed loop" system with monitoring wells in place allowed for ongoing analysis of the success of remediation throughout the site. The 140' by 210' (43 X 64 meter) infiltration gallery was placed above the zone of contamination in order to flush the underground soils and groundwater. The gallery consisted of roughly thirty 9" to 6' (23 centimeters to 3 meters) deep trenches filled with wash gravel, spaced from 5 to 10 feet (1.5 X 3 meters) apart inlaid with slotted 3" (8 centimeters) PVC effluent supply pipes. The gallery design in conjunction with recovery wells at the lower end of the contaminated plume allowed for a continual refiltering of the contaminated water. Leaving test wells in place throughout the cleanup process allowed for ongoing monitoring and the ability to operate the bioraeactors for as long as needed.

Remediation of contaminants on the southern portion of the SLR site began in January, 1993. The combined bioreactor and infiltration technique lasted approximately eleven months at a cost of roughly $1 million. Compared to a rough estimate of $2 million for the excavation and removal of contaminants which would have taken less than three months, the cost difference as well as the long term liability strongly favored the action taken. Because the bioremediation technique treated both groundwater and soils, its cost and timescale also compared favorably to other options that would have required dual faceted soil and groundwater remediation. By 1998, the site had been developed as light industry, housing D.C. Sales, a distributing company.

Conclusions

The successful use of bioreactor technology on the SLR related largely to the extensive testing and in-depth understanding of site characteristics. Important factors in this success were the nature of the porous soils, the ability to key in on a single contaminant of concern (gasoline), a relatively homogeneous subsurface geology which created an accessible and uniform plume pattern as well as clear controls over the changes in composition of influent from recovery wells. McCarty (1990) and Alexander (1994) indicate that the homogeneity of the subsurface geology is a critical factor in the effectiveness of any system of underground flushing. Due to the stability of the bedrock geology, the plume of contaminants was uniform and accessible. Where a plume is dissected, recovery of contaminants is problematic, and bioreactor technology is limited.

McCarty (1990) warns of negative chemical transformations that may occur with the use of bioreactor technology. If contamination on a site is composed of a complex of substances, then remediation for one type may negatively impact upon other substances present in the soil. For instance, a site contaminated with a combination of solvents such as acetone, carbon tetrachloride (CT), thichloroethene (TCE) and 1,1,1,-trichloroethene (TCA) would require careful scrutiny to assure that the byproducts of remediation presented no greater hazard than the contaminants themselves. In the above case, TCA may be reduced to 1,1-dichloroethane, chloroethane, acetate and 1,1-dichloroethene. TCE may be transformed into an isomer of dichloroethene and vinyl chloride. In each instance, the hazards of the by-product are assumed to exceed the hazards of the present toxin (McCarty, 1990). Again, the SLR site remediation was dealing with the BTEX compounds associated with gasoline, and thus far, this treatment appears effective and is without significant by product hazard. Though the by product issue must be considered prior to use in sites with a mix of compounds

In the SLR site, nutrients (N and P salts) were added to the system at the upper limits of effluent standards with apparently little negative impact. Alexander (1994) cautions against overloading a system with nutrients and creating the possibility for biomass to accumulate in quantities exceeding the limits of aquifer, thus clogging the flow of groundwater and bioreactor technology. On the SLR site, it appears that this was not an issue. However, pumping nutrients, particularly nitrogen, into a groundwater situation should be handled with care. Theoretically, the SLR and other sites are designed as closed loop systems, however, it is not inconceivable that some leakage would occur. As this issue is explored, perhaps wider testing of site boundaries may be necessary.

According to Larry Heinz at the MCDA, new technologies in bioreactors relate to the bioengineering of microbes to increase rates and success of biodegradation. In some cases, where little indigenous microbial activity remains, importation of microbes is a common practice. It is unclear, however, whether bioengineered microbes should be a cause for concern and no information relating to these concerns was encountered in the research of this paper.

In an effort to see the remediation and development of this site, MCDA and the MPCA allowed lead levels to exceed limits for residential development. This acceptance of excessive levels of this toxin may present difficulties into the future, as with any use of "capping". The toxin remains on site, and will limit future development. In this way, brownfields development in a climate that rewards only economic growth over full remediation means that future development limitations and site design criteria remain limited by partial remediation. In contrast, English landscape architect John Hopkins points out that since the British national government and regional bodies have a legal mandate to direct growth towards brownfields in an effort to retain agriculture and greenbelts, urban site remediation is generally performed to allow full mixed use (residential, commercial and industrial) of reclaimed land (personal conversation). Without these metropolitan area policies in the United States, individual cities will continue to address brownfields only to the extent that they are economically feasible, thus limiting their potential as fully integrated urban spaces.

The successful remediation of the southern portion of the SLR site using what was in 1990 a newly emerging technology was due largely to the nature of the toxins and physiology of the site itself as well as the cooperation of the MCDA, MPCA and EPA. By 1999, bioreactor technology is well established in the cleanup of BTEX contaminated sites. The encouraging news from this case study is that in the United States, more than 275,000 leaking underground storage tank sites have been identified, and bioreactor technology for their cleanup offers hope for full remediation. Older sites, however, usually contain lead as an added toxin, which presents further challenges for remediation. In the future, combining bioreactors with in-situ phytoremediation, chemical immobilization or removal technologies should be considered to allow for greater urban opportunities beyond the limited scope of light industrial development based on partial remediation.

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