

# **THE BIOREMEDIATION OF MTBE WITH OXYGEN RELEASE COMPOUND (ORC<sup>®</sup>)**

Stephen S. Koenigsberg and Rick Gillespie, Regenesis, San Clemente, CA  
([steve@regenesis.com](mailto:steve@regenesis.com) [rick@regenesis.com](mailto:rick@regenesis.com))  
William R. Mahaffey, Pelorus, Evergreen, CO ([mahaffwr@worldnet.att.net](mailto:mahaffwr@worldnet.att.net))

## **ABSTRACT**

MTBE complicates remediation and closure of properties contaminated with BTEX and other fuel hydrocarbons. Regulators and oil companies are becoming increasingly concerned about the environmental impact of MTBE, because some of its physical properties compromise active remediation methods such as air sparging and pump and treat systems. One of the options to address these limitations is in-situ aerobic bioremediation, which can be enhanced by ORC (Oxygen Release Compound). Several years ago, consultants using ORC noticed that MTBE concentrations decreased at an unusually high rate, relative to the literature in monitoring wells containing ORC filter socks. Working on this empirical foundation, a number of subsequent laboratory and field experiments have demonstrated that oxygen can enhance the remediation of MTBE. These basic results and the implications will be discussed in detail. Also, some special features of the work, such as the role of co-oxidative mechanisms and competitive inhibition in MTBE bioremediation will be elucidated.

## **INTRODUCTION**

As a ubiquitous fuel additive, methyl tert-butyl ether (MTBE), has complicated the remediation and closure of contaminated properties. Regulators, oil companies, and now the public are becoming increasingly concerned about the environmental impact of this and other related ether oxygenates. Several factors responsible for the heightened level of concern include the following: 1) MTBE degrades very slowly under natural conditions, 2) it has a very low taste and odor threshold, 3) its toxicity and carcinogenicity profile are largely undetermined and 4) it is highly soluble and does not readily retard on the aquifer matrix. This last feature has compromised active remediation methods (air sparging and pump and treat) because of inefficiencies in stripping. As a result, many consultants have turned to other treatment options – most notably in-situ aerobic bioremediation.

Active in-situ aerobic bioremediation, designed to accelerate rates of natural attenuation, requires supplemental oxygen. One option in achieving this is the use of Oxygen Release Compound (ORC). ORC is a patented formulation of time-release magnesium peroxide that releases oxygen slowly when hydrated. ORC treatment represents a “low intensity” approach to in-situ aerobic bioremediation; it is simple to apply, operates passively and is very low in cost because its use dramatically limits design, capital and operating expenses. One application of ORC typically lasts 6 months

to one year depending on site conditions. Its ability to reduce time to site closure has been documented via its use at 6,500 sites in 50 states and 12 countries. There is also a full body of independent, peer reviewed literature on its performance, which can be accessed at [www.regenesis.com](http://www.regenesis.com).

ORC is applied using exchangeable filter socks or as a loose powder. Filter socks are placed in an array of wells or trenches, after which contact with ground water promotes the formation of an “oxygen barrier” that facilitates plume cut-off. ORC powder can be made into a slurry for permanent applications in the saturated zone, or dispersed as free powder for the in-situ or ex-situ treatment of soil. A broad array of treatment points, in which ORC slurry is backfilled or injected, can be implemented with low-cost, small-bore injection or auguring methods. Loose powder is traditionally used in the remediation of residual contamination at the bottom of tank excavations. The first and most dominant applications of ORC were for the treatment of BTEX compounds and other petroleum hydrocarbons. Use has now expanded to the remediation of certain chlorinated compounds, such as vinyl chloride and ethers such as MTBE. A more complete review of the technology can be found in reference (1).

## **ESTABLISHING THE EFFICACY OF ORC IN THE FIELD**

The observation that ORC could be used in the treatment of MTBE came fortuitously. In 1996, at a time when MTBE was not being regulated, we would encounter an occasional consultant who would be particularly thorough and analyze groundwater for “everything”. As a result, MTBE levels would sometimes be reported in conjunction with conventional BTEX and TPH data in the course of tracking the performance of ORC. When we investigated the issue more closely we realized that MTBE was a potential concern and that it was degrading at a faster rate than would be expected in accordance with published rates (2). These data are presented in Table 1 and represent the exposure of the contaminants to fairly high levels of dissolved oxygen (20-30 ppm), in wells where ORC socks were being applied. Combined with the fact that stripping is not possible, especially with a slow release of oxygen, the hypothesis emerged that ORC was facilitating the aerobic bioremediation of MTBE by increasing levels of dissolved oxygen in the aquifer. This hypothesis was formulated in large part due to the foundation work of Salanitro et al., (3) in which it was shown that a bacterial consortium was capable of complete aerobic degradation of MTBE. This work in turn was founded on a variety of reports involving the aerobic degradation of other ethers and a series of inconclusive studies pertaining to the aerobic and anaerobic degradation of MTBE itself.

Subsequent to these field observations, which were reported by Koenigsberg (4), other oxygen-mediated bioremediation field evidence appeared in presentations by Javanmardian and Glaser (5) and by Carter et al., (6). These studies reported remediation of MTBE by air and oxygen sparging respectively. Following this, as MTBE became more of a regulatory concern, other data sets supporting the hypothesis that ORC could

facilitate the remediation of MTBE were being accumulated. A summary of these earliest results, from remediations that occurred in 1996-1997 are presented in Table 2.

Examining Case #4 in more detail as an example, ORC was applied as a slurry at a service station in Lake Geneva, WI. At a site in Grafton, WI, there were actionable levels of MTBE and BTEX due to a leaking UST. Though the UST was removed and the contaminated soil excavated, MTBE and BTEX still persisted in the groundwater. 1,700 pounds of ORC was applied via direct-push technology, to enhance aerobic degradation in the saturated zone. The MTBE degradation results are presented in Figure 1.

## **SUPPORTING THE FIELD OBSERVATIONS WITH LABORATORY RESULTS**

Subsequent to the work of Salanitro et al. (3), which presented the more general evidence for the role of aerobic processes, there was a specific report by Park and Cowan (7), which established and quantified a clear link between oxygen in the bioremediation of MTBE. As a result, Regensis commissioned studies at the University of California at Riverside with Marc Deshusses and Nathalie Fortin to corroborate these findings. The intent was to offer some evidence, under controlled conditions, that oxygen indeed was the limiting factor in the rate of MTBE biodegradation. The studies as reported in Koenigsberg et al. (8), investigated the biodegradation of MTBE by respirometry. In the experiment, oxygen uptake rates at various dissolved oxygen concentrations were used to quantify the influence of dissolved oxygen concentration on the rate of MTBE biodegradation. Results of the experiment demonstrated 1) the rate of MTBE biodegradation was proportional to the concentration of dissolved oxygen in water and 2) MTBE uptake followed a Michaelis-Menten kinetics with respect to dissolved oxygen.

## **SPECIAL BIOCHEMICAL CONSIDERATIONS IN THE OXYGEN-MEDIATED BIODEGRADATION OF MTBE**

As additional data sets were reviewed, an interesting pattern emerged. In many, although not all cases, it appeared that when MTBE and background hydrocarbons (typically BTEX) were co-mingled, the BTEX was preferentially remediated and its concentration had to drop before significant MTBE degradation could proceed. Prompted by such field results, a series of laboratory experiments were conducted to test whether background hydrocarbons interfere with MTBE degradation. If so this would be a case of classical competitive inhibition and if proved true would be an important finding, because it would mean that oxygen supplementation would have dual value. In other words, oxygenation could now be used to facilitate the removal of competing hydrocarbons as well as MTBE itself.

To test the hypothesis, aerobic bacteria known to be capable of degrading MTBE and BTEX were isolated with the assistance of Don Phipps at the Orange County Water

District, Fountain Valley, CA. These bacteria were able to exist on a medium with MTBE as the sole carbon source. In the experiment, performed by William Farone of APC in Anaheim, CA, the MTBE degraders were challenged with xylene as a representative BTEX hydrocarbon (relative to the chromatographic methods xylene could be handled conveniently in relation to MTBE on the same column). The results showed that MTBE degradation was inhibited by xylene; during a seven day period there was a 52% reduction of MTBE in the absence of xylene versus a 9% reduction of MTBE with xylene present.

More advanced studies were then conducted by William Mahaffey of Pelorus EnBiotech in Evergreen, CO. His work explored the hypothesis that MTBE biodegradation is 1) an aerobic co-oxidative process and 2) that competitive inhibition could exist between a primary substrate and MTBE and 3) that co-oxidation of MTBE may be limited by the availability of reducing equivalents required by the initial oxygenase enzyme system. A working hypothesis was advanced based on structure activity relationships and an assumption that the most likely primary substrates involved in co-oxidation and competitive inhibition are compounds found at the aerobic fringe of a petroleum hydrocarbon plume. Thus target substrates for co-oxidative metabolism of MTBE were; methane, alkanes, cycloalkanes, benzene and o-xylene. Initial studies, using resting cell transformation tests, demonstrated that substantial removal of MTBE was achieved with cultures that were acclimated to benzene, camphor, o-xylene and cyclohexanone (Mahaffey, unpublished). In these early tests a specific benzene acclimated culture, designated PEL-B201, was found to be most efficient in degrading MTBE (58% removal). This established the possibility that a single enzyme system could metabolize both MTBE and a primary substrate thus being under the influence of competitive inhibition dynamics. Support for the competitive inhibition hypothesis was obtained by demonstrating both MTBE inhibition of benzene metabolism and the inhibition of MTBE metabolism with increasing benzene concentrations. Subsequent studies (8) demonstrated clearly that MTBE inhibits oxygen uptake associated with benzene metabolism (Table 3).

Biotransformation experiments performed with benzene acclimated cell suspensions are presented in Figure 2. Benzene induced cell suspensions degrade >99% of the added MTBE, while increasing levels of benzene (1.9 uM and 3.8 uM) resulted in a significant reduction in the rates of MTBE degradation. No degradation of MTBE was observed with cells grown on the non-inducing substrate succinate. The lack of MTBE degradation on succinate grown cells demonstrated that the MTBE metabolism occurs with an enzyme system associated with benzene metabolism and reaffirmed the hypothesis that MTBE is metabolized by co-oxidation.

# **OXYGEN UPTAKE RATES (OUR) WITH RESTING CELL SUSPENSIONS OF THE BENZENE DEGRADING BACTERIAL CULTURE PEL-B201**

Unpublished studies conducted at Pelorus have indicated that o-xylene degrading pure cultures will also efficiently degrade MTBE via a co-oxidative mechanism. Some preliminary results indicate that the most efficient MTBE co-oxidizing cultures possess what maybe a novel pathway of o-xylene metabolism. Studies have established that oxidation of the aromatic nucleus of o-xylene was the primary mechanism of attack. However, the formation of o-toluic acid and 2,3-dihydroxy-o-toluic acid suggested that attack of the methyl group substituent also occurs.

Several strains of o-xylene degrading organisms have been shown to be simultaneously adapted to degradation of o-phthallic acid. It is not clear at this time what the ring fission mechanism is for these organisms, however they are the most active MTBE degraders. Inspection of space filling molecular models of MTBE and o-xylene indicate that the MTBE methyl groups can be aligned in the same plane as the o-methyl groups of o-xylene. This allows for speculation that MTBE could bind to the o-xylene oxygenase active site in a manner that they may align the methyl groups in the appropriate configuration for oxidative attack. Studies such as these continue to expand the possible mechanisms available to microorganisms for the degradation of MTBE in the environment.

## **CURRENT STATUS OF OXYGEN-MEDIATED MTBE BIOREMEDIATION**

In a second wave of field activity, several end users of ORC published papers on their results. These include Boyle et al. (9), Buzea and DeStefanis (10), and Defibaugh and Fishman (11). In one of the studies (10), BTEX and MTBE contamination in a fine grained sediment was treated with ORC through a series of push-point injections. Data from the wells within the sphere of influence of the treatment, over a seven month period, is presented in Table 4.

Since these studies a number of other major field projects have been executed. Recently, Patrick Hicks and Michelle Pahr of Arcadis Geraghty and Miller, in collaboration with J.P. Messier of the U.S. Coast Guard, performed a full-scale *in situ* bioremediation of dissolved phase MTBE and BTEX at a USCG facility in Elizabeth City, NC. At the facility, three 10,000-gallon fiberglass underground storage tanks (USTs) had leaked and, after excavation and removal of the USTs, free phase Jet Fuel (JP-5) and groundwater were observed in the bottom of the excavation. Depth to groundwater at the site is approximately 2 m below land surface (bls). The goal of the project was to enhance the natural attenuation of dissolved petroleum constituents without interfering with facility operations.

Aquifer oxygenation was accomplished by injecting ORC into the contaminated aquifer. The source area near a former UST was treated with 18 injection points. Each source area injection point received a slurry suspension of 35 pounds of ORC. The plume portion was treated with 13 injection points. Each plume area injection point received a slurry suspension of 22 pounds ORC. A secondary treatment event in the plume area included 16 injection points. Each injection point received a slurry suspension of approximately 33 pounds of ORC.

Post treatment monitoring of the aquifer indicated the dissolved MTBE mass was reduced 100% in both the source and plume areas. The dissolved BTEX mass was reduced 99% in the source area, and 53% in the plume area. Site closure has been obtained from the North Carolina Department of Environment and Natural Resources, Division of Environmental Management.

With respect to ORC barriers, a major field research study was conducted by Barcelona and Jaglowski (12). In the study, an in-situ reactive tracer test was conducted at the former Wurtsmith AFB in Oscoda, MI. An ORC oxygen barrier was constructed and over 11,000 measurements were taken at over 3,500 locations and times during an 8-month period. The results were marginally positive with the authors stating that “evidence exists for the degradation of MTBE through TBA in a highly oxidizing environment” while also noting that “MTBE has been observed to degrade under suboxic conditions”. Since there is other supporting evidence for anaerobic degradation of MTBE, although the role of aerobes is much less equivocal at this time, both mechanisms may have been operating in this system.

With respect to the ORC barrier, it produced a significant level of oxygen (20-30 ppm), however the groundwater flow rate was fairly high (1.3 ft./day) and this limited residence time in the barrier zone. Additionally, the experimentally constructed plume, which was created upgradient and allowed to migrate toward the barrier, hit the barrier at very low ppb concentrations. Being at the “tail end of the asymptote” can be problematic with respect to seeing significant degradation in a short residence time. The lesson learned was that when barriers are used they would be more effective in combating higher concentration and/ or lower flow rate regimes.

Eventually, that opportunity presented itself through the work of James Landmeyer and his colleagues at the U.S. Geological Survey Office in Columbia, SC. The following is a synopsis of the first intensive and definitively positive ORC barrier study as prepared by Landmeyer.

“Microbial communities indigenous to a shallow ground-water system near Beaufort, South Carolina were observed to degrade milligram per liter concentrations of methyl *tert*-butyl ether (MTBE) under natural and artificial oxic conditions (13). Significant MTBE biodegradation was observed where anoxic, MTBE-contaminated ground water discharged to a concrete-lined ditch. In the anoxic ground water adjacent to

the ditch, concentrations of MTBE were greater than 1 mg/L. Where ground water discharge occurs, dissolved oxygen (DO) concentrations beneath the ditch exceeded 1.0 mg/L to a depth of 1.5 meters, and MTBE concentrations decreased to less than 1 µg/L prior to discharge. MTBE mass flux calculations indicate that 96% of MTBE mass loss occurs in the relatively small oxic zone prior to discharge. Samples of a natural microbial biofilm present in the oxic zone beneath the ditch completely degraded [U-<sup>14</sup>C] MTBE to <sup>14</sup>C-CO<sub>2</sub> in laboratory liquid culture studies, with no accumulation of intermediate compounds. Upgradient of the ditch in the anoxic, MTBE and BTEX-contaminated aquifer, addition of a soluble oxygen release compound resulted in oxic conditions and rapid MTBE biodegradation by indigenous microorganisms. In an observation well located closest to the oxygen addition area, DO concentrations increased from 0.4 to 12 mg/L in less than 60 days and MTBE concentrations decreased from 20 to 3 mg/L. In the same time period at a downgradient observation well, DO increased from less than 0.2 to 2 mg/L and MTBE concentrations decreased from 30 to less than 5 mg/L.”

“This biodegradation of MTBE in a shallow ground-water system at locations of natural and artificial oxic conditions is important in light of the large amount of evidence that exists suggesting that MTBE is relatively recalcitrant in many ground-water systems, and that MTBE would therefore preferentially accumulate. Those studies indicated that the success of bioremediation strategies such as natural attenuation would likely be low in plumes containing MTBE, and that remediation could only occur if contaminated aquifers were inoculated with specific microorganisms derived from enrichment cultures shown to degrade MTBE. However, the results of this study demonstrate that significant natural attenuation of MTBE can occur if the oxygen limitations naturally associated with gasoline releases can be removed, either under natural conditions where discharging anoxic ground water comes into contact with oxygen, or artificial conditions where oxygen can be added to aquifers containing mg/L concentrations of MTBE. This final solution may be an effective strategy for intercepting characteristically long MTBE plumes, particularly at those sites not characterized by ground-water discharge to land surface.”

## CONCLUSION

Presently, there is a significant and growing body of evidence that oxygen enrichment of the sub-surface can facilitate the remediation of MTBE. This paper has documented the first evidence for the efficacy of field applications of oxygen, in this instance through the use of a time-release oxygen technology, ORC. Also, new contributions to understanding basic biochemical mechanisms of degradation that are oxygen dependent have been offered. These results were unfolded from a number of extant commercial data sets, with the support of the fundamental laboratory studies as cited. In addition to the use of ORC, others as cited have supported the essential conclusions through the use of sparged air or oxygen in their field work, and most recently, there have been two widely recognized, large-scale studies in this area (14 ; 15).

The decision to use of ORC or sparging to achieve desired objectives involves a basic series of economic and practical considerations and is beyond the scope of this paper. While it will be left to the consultant to sort out the exact needs which are highly case dependent, the advantages of having a passive, low cost and long term option for supplemental oxygenation is compelling. ORC technology seems particularly attractive for plume cut-off strategies by employing an easily injectable oxygen barrier. The total installed cost (injection and materials) for a barrier that is 100 feet in length and 10 feet into the aquifer is about \$10,000 with variable yearly replacement requirements.

In the broader sense both ORC and sparging oxygenation technologies have established the essential fact that MTBE is aerobically biodegradable under field conditions and that accelerating the natural attenuation of MTBE by providing supplemental oxygen is a valid and important engineering objective in site management.

# TABLES AND FIGURES

## Tables

Table 1: Initial Observations on the Impact of ORC on MTBE: Composite Results for 1<sup>st</sup> Quarter 1996

Table 2: Regeneration Field Programs Results

Table 3: MTBE Inhibition of Oxygen Uptake Associated with Benzene Metabolism

Table 4: Concentration Reductions of MTBE and BTEX

## Figures

Figure 1: MTBE Reduction at 2 Wells in Lake Geneva, Wisconsin

Figure 2: Competitive Inhibition of MTBE Cooxidation

# TABLES

Table 1.

Initial Observations on the Impact of ORC on MTBE Composite Results for 1st Quarter 1996		
Monitoring Well	k/day BTEX	k/day MTBE*
Site 1 (well #1)	0.1209	0.0841
Site 1 (well #2)	0.0479	0.0790
Site 1 (well #3)	0.0548	0.0112
Site 2 (well #1)	0.0383	0.0257
Site 3 (well #1)	0.6161	0.0432
Site 4 (well #1)	(0.0108)	0.0854
Site 4 (well #2)	0.0636	0.0306
Site 5 (well #1)	0.0671	0.0912
Site 5 (well #2)	0.0577	0.1447

\* Howard et al. (1991), in his reference book on degradation rates, reports that MTBE degrades at a rate between 0.0038 and 0.0231. These rates probably reflect measurements in a range of natural conditions from anaerobic through microaerophylic to aerobic.

Table 2.

Regenesis Field Program Results						
Site	Location	ORC Application	Time (days)	Monitoring Well Distance from ORC Placement	% Reduction BTEX	% Reduction MTBE
1	PA	Slurry Injection	138	MW 1 - 60'	66%	70%
2	NJ	Barrier	182	MW 1 - 4'	24%	26%
				MW 3 - 4'	73%	99%
3	NJ	Slurry Injection	393	MW 1 - 7'	100%	90%
				MW 2 - 50'	100%	86%
				MW 3 - 85'	100%	100%
4	WI	Slurry Injection	280	MW 2 - 7'	100%	100%
				MW 3 - 13'	90%	99%
5	WI	Tank Pit Treatment & Injection	440	MW 1 - 4'	68%	78%
6	MA	Slurry Injection	187	MW 1 - 5'	100%	100%

**Table 3. MTBE Inhibition of Oxygen Uptake Associated with Benzene Metabolism**

$\mu\text{M}$ Benzene	$\mu\text{M}$ MTBE	nMoles- O <sub>2</sub> /min	Percent Inhibition	Comments
0	0	14.20	0	Endogenous rate on residual growth substrate
0	10	9.40	33.8 %	MTBE Inhibition of endogenous activity
0	100	7.50	47.2 %	"
50		23.80	-	Primary substrate activity
100		27.50	-	"
250		30.80	-	:
50	100	12.50	47.5 %	MTBE Inhibition of primary substrate activity
100	100	13.90	49.5 %	"
250	50	17.00	44.8 %	"

**Table 4. Concentration Reductions of MTBE and BTEX**

Adapted from Buzea, D.C. and DeStefanis. E.J. 1999. Accelerated bioremediation as an alternative to conventional remedial technologies In: In Situ Bioremediation of Petroleum Hydrocarbon and Other Organic Compounds (Alleman, B.C. and Leeson, A), Eds.), © Battelle Press, Columbus, OH

Sample ID	Date	BTEX (ug/L)	MTBE (ug/L)
TB-1	4/2/1997	54,100	1,300
TB-1	8/27/1997	30,200	< 500
TB-1	11/17/1997	32,300	180
TB-3	4/2/1997	206,200	10,000
TB-3	8/27/1997	39,300	6,900
TB-3	11/17/1997	9,900	4,800
TB-5	4/2/1997	93,100	33,000
TB-5	8/27/1997	61,100	4,900
TB-5	11/17/1997	45,400	5,600
TB-6	4/2/1997	99,000	22,000
TB-6	8/27/1997	52,300	3,800
TB-6	11/17/1997	58,300	2,400
TB-7	4/2/1997	20,570	540
TB-7	8/27/1997	1,360	76
TB-7	11/17/1997	34,400	300

# FIGURES

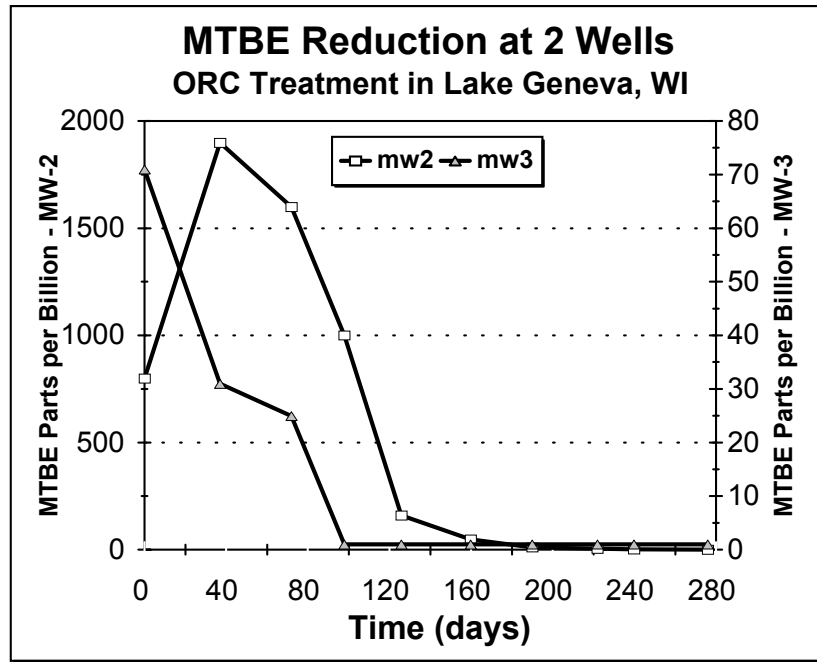


Figure 1.

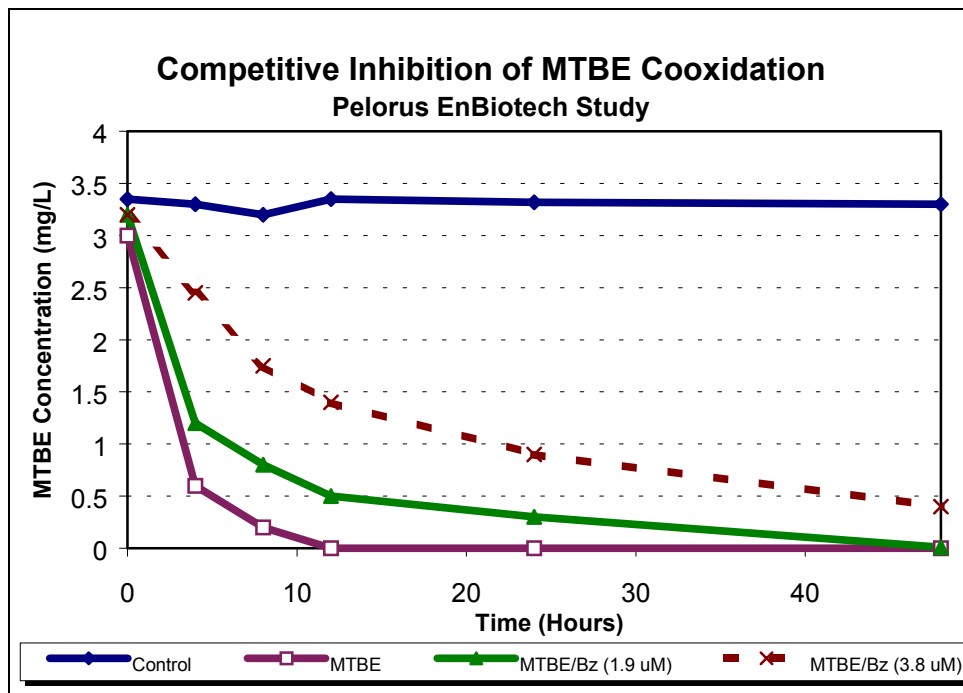


Figure 2.

## REFERENCES

1. Koenigsberg, S.S. and C.A. Sandefur. "The Use of Oxygen Release Compound for the Accelerated Bioremediation of Aerobically Degradable Contaminants: The Advent of Time-Release Electron Acceptors." *Remediation Journal*. Winter, pp. 3-29 (1999).
2. Howard, P.H., Boethling, R.S., Jarvis, W.F., Meylan, W.M. and E.M. Michaelenko. "Handbook of Environmental Deradation Rates." Lewis Publishers: Boca Raton, FL. (1991).
3. Salanitro, J.P., Diaz, L.A., Williams, M.P. and H.L. Wisniewski. Isolation of a Bacterial Culture that Degrades Methyl t-Butyl Ether. *Applied Environmental Microbiology*. **60** (7): 2593-2596. (1994).
4. Koenigsberg, S. 1997. "Enhancing Bioremediation: New Magnesium Peroxygen Compound Accelerates Natural Attenuation." *Environmental Protection*, February (1997).
5. Javanmardian, M. and H.A. Glasser. "In Situ Biodegradation of MTBE Using Biosparging. Proceedings of the American Chemical Society Division of Environmental Chemistry", April 13-17, San Francisco, CA. (1997).
6. Carter, S.R., Bullock, J.M. and W.R. Morse. "Enhanced Biodegradation of MTBE and BTEX using Pure Oxygen Injection." *In Situ and On Site Bioremediation*. Alleman, B.C. and A. Leeson (Eds.). Battelle Press: Columbus, OH. **4**(4):147. (1997).
7. Park, K. and R.M. Cowan. "Effects of Oxygen and Temperature on the Biodegradation of MTBE." In Preprints of Extended Abstracts, Proceedings of the 213<sup>th</sup> ACS National Meeting, San Francisco, CA. **(37)1**:421-423. (1997).
8. Koenigsberg, S.S., C.A. Sandefur, W.R. Mahaffey, M. Deshusses and N. Fortin. "Peroxygen mediated bioremediation of MTBE." *In Situ Bioremediation of Petroleum Hydrocarbon and Other Organic Compounds*. Alleman, B.C. and Leeson, A. (Eds.). Battelle Press: Columbus, OH. **5**(3):13-18. (1999).
9. Boyle, D., Goers, M., Mandava, S., Hicks, P., Lemons, K., Pendrell, D. and M. Canfield. "Enhanced In-Situ Bioremediation of Groundwater at Macdill Air Force Base, FL." *In Situ Bioremediation of Petroleum Hydrocarbon and Other Organic Compounds*. Alleman, B.C. and A. Leeson (Eds.). Battelle Press: Columbus, OH. **5**(3):287-294. (1999).
10. Buzea, D.C. and DeStefanis. E.J. "Accelerated bioremediation as an alternative to conventional remedial technologies." *In Situ Bioremediation of Petroleum Hydrocarbon and Other Organic Compounds*. Alleman, B.C. and Leeson, A. (Eds.). Battelle Press: Columbus, OH, **5**(3):427-432. (1999).

11. Defibaugh, S.T. and Fishman, D.S. "Biodegradation of MTBE Utilizing a Magnesium Peroxide: a Case Study." In *Situ Bioremediation of Petroleum Hydrocarbon and Other Organic Compounds*. Alleman, B.C. and Leeson, A. (Eds.). Battelle Press: Columbus, OH. **5(3)**:1-6.
12. Barcelona, M. J., and Jaglowski, D. R. "Subsurface Fate and Transport of MTBE in a Controlled Reactive Tracer Experiment." *Proceedings of the 2000 Petroleum Hydrocarbon and Organic Chemicals in Ground Water: Prevention, Detection, and Remediation*. November, pp. 123-137. (1999).
13. Landmeyer, J.E., Chapelle, F.H., Herlong, H.H. and P.M. Bradley. "Methyl tert-Butyl Ether Biodegradation by Indigenous Aquifer Microorganisms Under Natural and Artificial Oxidic Conditions." *Environmental Science & Technology*. **35(6)**: 1118-1126. (2001).
14. Salanitro, J., Spinnler, G., Maner, P., Wisniewski, H. and P. Johnson. "Potential for MTBE Bioremediation- In Situ Inoculation of Specialized Cultures." *Proceedings of the API/NGWA Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection and Remediation Conference*, November 17-20, Houston, TX. (1999).
15. Mackay, D.M., Einarson, M.D., Wilson, R.D., Fowler, B., Scow, K., Hyman, M., Naas, C., Schirmer, M. and G.D. Durrant. "Field Studies of In-Situ Remediation of an MTBE Plume at Site 60, Vandenberg Air Force Base, California." *Proceedings of the 2000 Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Remediation*. (1999).