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RESEARCH-BASED • SEPTEMBER 2026

1. The anchor article and its abstract

The central finding: a solid magnesium-peroxide formulation did more than remove existing sulfide. Its gradual oxygen release raised ORP and inhibited the sulfate-reducing conditions that allow hydrogen sulfide to reform.

A method for controlling hydrogen sulfide in water by adding solid phase oxygen

Yu-Jie Chang, Yi-Tang Chang & Hsi-Jien Chen
Bioresource Technology 98 (2007) 478–483 • DOI 10.1016/j.biortech.2005.11.031

PUBLISHED ABSTRACT

This work evaluates the addition of solid phase oxygen, a magnesium peroxide (MgO_2) formulation manufactured by Regenesis (oxygen-releasing compounds, ORC™), to inhibit the production of hydrogen sulfide (H_2S) in an SRB-enriched environment. The initial rate of release of oxygen by the ORC was determined over a short period by adding sodium sulfite (Na_2SO_3), which was a novel approach developed for this study. The ability of ORCs to control H_2S by releasing oxygen was evaluated in a bench-scale column containing cultured sulfate-reducing bacteria (SRB). After a series of batch tests, 0.4% ORC was found to inhibit the formation of H_2S for more than 40 days. In comparison, the concentration of H_2S dropped from 20 mg S/L to 0.05 mg S/L immediately after 0.1% hydrogen peroxide (H_2O_2) was added, but began to recover just four days later. Thus, H_2O_2 does not seem able to inhibit sulfide production for an extended period. By providing long-term inhibition of the SRB population, ORC provides a good alternative means of controlling H_2S production in water.

Chemical notation and line breaks standardized from the published abstract.

4 DAYS	>40 DAYS	DAY 50	>60 DAYS
H_2O_2 rebound began	**Duration stated in abstract**	**MgO_2 held sulfide below 4 mg S/L**	**Duration stated in conclusion**

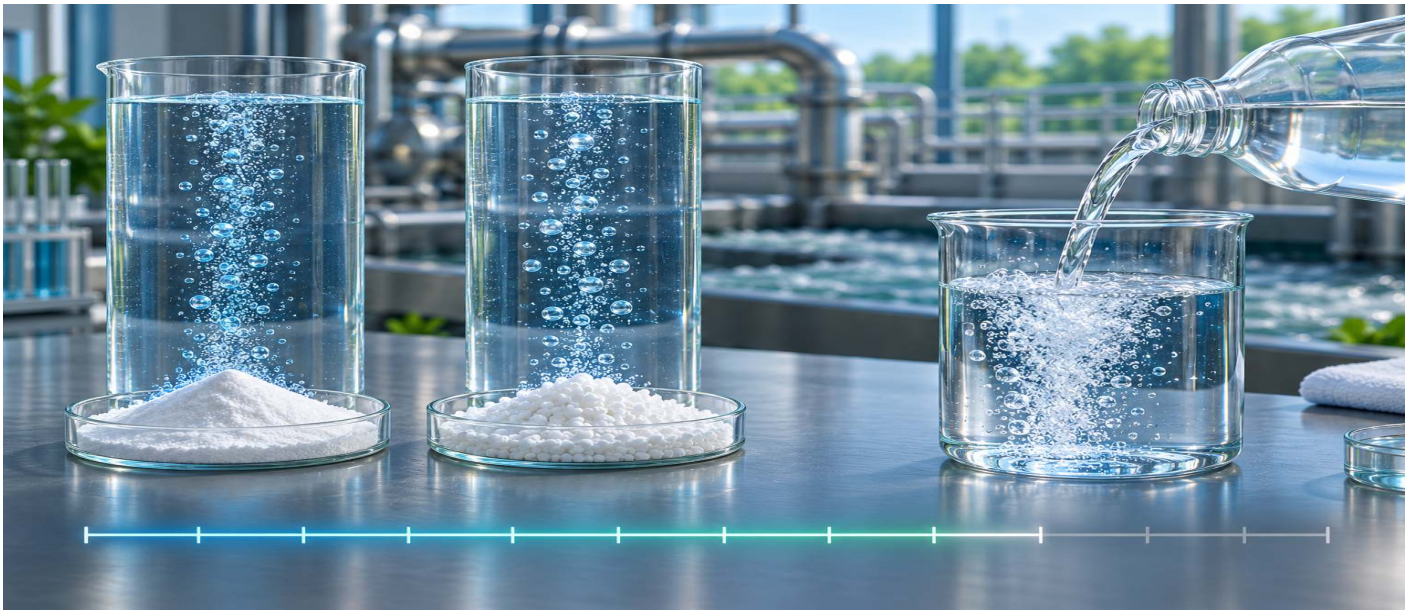
How to read the duration: “more than 40 days” is the abstract’s summary; day 50 is the reported performance checkpoint; and “more than 60 days” is the authors’ concluding statement. These are complementary statements from different sections—not conflicting treatment guarantees.

Scope: This paper synthesizes primary research on MgO_2, CaO_2 and related wastewater synergies. Study results are not product guarantees. Full-scale dose, interval and economics must be validated under site hydraulics and demand.

CHEMISTRY

2. Three chemistries. Distinct operating profiles.

Available oxygen describes how much oxygen a formulated product can deliver; release profile describes how quickly that capacity reaches the water. The comparison below uses total product mass for all three chemistries and separates capacity from operating behavior.



ATTRIBUTE	MgO_2 — SOLID	CaO_2 — SOLID	H_2O_2 — LIQUID SOLUTION
Release profile	Controlled release; product literature reports months to approximately one year*	Controlled release; engineered formulations report more than 350 days*	Fast reaction; no long-lived oxygen reservoir in high-demand water
Coproduct	$Mg(OH)_2$	$Ca(OH)_2$	Water
Process leverage	ORP + alkalinity + magnesium chemistry	ORP + alkalinity + calcium/phosphate chemistry	Immediate oxidation and shock response
Available O_2 by total product mass*	10–11% by mass	17–18% by mass PeroxiCal™: ≥18%	25% solution: 11.8% by mass 50% solution: 23.5% by mass

Idealized net oxygen-release equations: $2MgO_2 + 2H_2O \rightarrow 2Mg(OH)_2 + O_2$ | $2CaO_2 + 2H_2O \rightarrow 2Ca(OH)_2 + O_2$ | $2H_2O_2 \rightarrow 2H_2O + O_2$

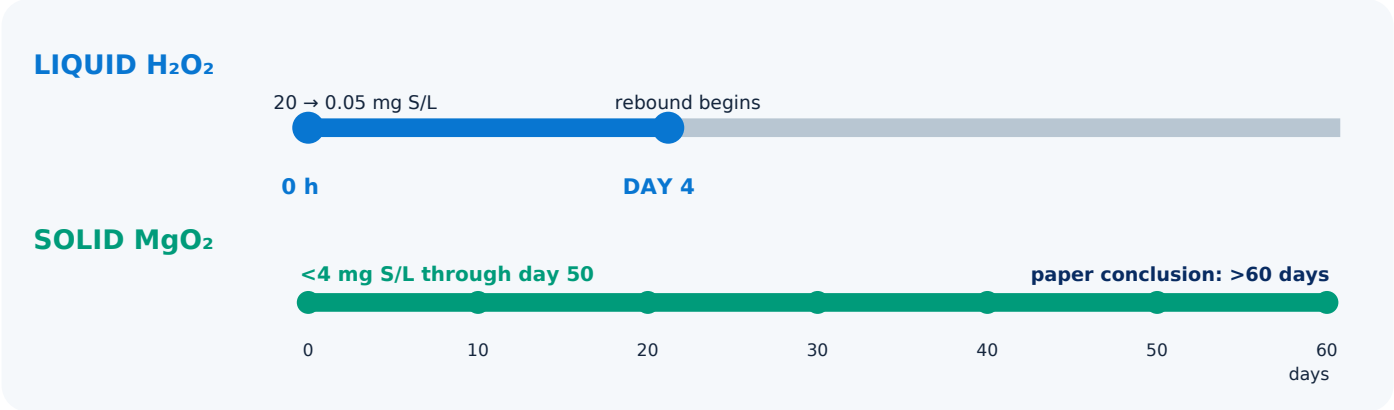
*All three equations are atom-balanced. Metal-peroxide oxygen release proceeds through hydration/hydrolysis and hydrogen-peroxide intermediacy; the equations shown are the overall net result. Equal formulated-product basis: representative magnesium-peroxide formulations provide approximately 10–11% available oxygen by total product mass; PeroxiCal™ provides ≥18%. H_2O_2 values are concentration-adjusted: 25% × 47.04% = 11.76%; 50% × 47.04% = 23.52%. Pure-compound maxima—28.4% MgO_2, 22.2% CaO_2 and 47.0% H_2O_2—are not the displayed comparison. Manufacturer release-duration claims come from subsurface-remediation applications; wastewater duration depends on formulation, demand, pH, temperature, mixing and hydraulics.

3. Why “fast” is not the same as “lasting”

A method for controlling hydrogen sulfide in water by adding solid phase oxygen

Chang, Chang & Chen • Bioresource Technology 98 (2007) 478-483 • DOI 10.1016/j.biortech.2005.11.031

The study used SRB-enriched laboratory columns and measured sulfide, sulfate, ORP and microbiological response. It compared a commercial MgO_2 formulation with liquid H_2O_2. The timeline below reports the paper’s stated milestones; it is not a reconstructed raw-data curve.



WHAT H_2O_2 DID

A 0.1% dose oxidized existing sulfide immediately-from about 20 to 0.05 mg S/L. Sulfide began to recover after day 4 and approached 10 mg S/L within 10 days.

WHAT MgO_2 DID

Cumulative 0.4% solid-phase formulation held sulfide below 4 mg S/L through day 50 and inhibited formation for >60 days in the conclusion.

WHY IT LASTED

The authors attributed control to both abiotic oxidation and biotic inhibition: oxygen release raised ORP and made conditions less favorable to SRB.

Precision note: “>40 days” appears in the abstract; “below 4 mg S/L through day 50” appears in the results; “>60 days” appears in the conclusion. The study does not establish a universal field interval and did not test calcium peroxide or OCPE-branded products.

4. What later studies add

The literature extends the solid-oxygen concept from bench SRB control into sewer reactors, chemical synergy and solids treatment. Results below retain the original test context.

APPLICATION	CHEMISTRY	QUANTIFIED FINDING	DESIGN TAKEAWAY
SRB inhibition	MgO_2 / formulation	Lower sulfide, SRB abundance and sulfate-reduction rate; higher ORP.[2]	Track biological prevention and sulfide removal together.
Rising main	CaO_2	One 0.2% w/v treatment with 12-h exposure reduced average sulfide and methane 80% over one week.[3]	One program may address odor, corrosion and methane.
Gravity sewer	CaO_2 + nitrate	Improved sulfide control and reduced CO_2/CH_4 relative to solo treatments.[4]	Pair electron acceptors and microbial pathways.
Gravity sewer	CaO_2 + Fe^{2+}	Reported cost: 31.3% of CaO_2-alone and 63.4% of Fe^{2+}-alone under study conditions.[5]	Combine radical chemistry, iron capture and inhibition.
Septic sewage	CaO_2; $FeCl_3$ + $Mg(OH)_2$	CaO_2 best individual reagent; combination removed >95% H_2S and saved 12% versus CaO_2 using historical local prices.[6]	Economics are site- and time-specific; mechanism stacking is transferable.
Dewatering	CaO_2 + re-flocculation	Improved filtration at optimum 20 mg/g TSS bench dose.[7]	Oxidize, then rebuild a drainable floc.
Co-digestion	CaO_2 pretreatment	At 0.14 g/g VSS: methane +37.4%, VSS destruction +38.9%, sludge reduction +19.9% in BMP tests.[8]	Balance solubilization against dose, oxygen and digester goals.
P management	CaO_2	Calcium accelerated phosphate fixation during WAS disintegration.[9]	Potential co-benefit; verify Ca:P, pH and solids destination.

Evidence boundary. Most results are laboratory or bench scale. They demonstrate mechanisms and plausible operating value, not universal dose or full-scale return on investment.

5. Stack mechanisms-not just chemicals

The strongest programs give each component a distinct job. Synergy should be tested with each component alone, the combination, and an untreated control.

1 OXYGEN + ALKALINITY

MgO_2 or CaO_2 supplies oxidizing capacity while $Mg(OH)_2$ or $Ca(OH)_2$ shifts pH and buffering. Two levers act on sulfide formation and release.

2 CaO_2 + NITRATE

Oxygen/alkalinity suppresses SRB while nitrate supports nitrate-reducing sulfide oxidation. The 2023 study also reported lower methane and CO_2.[4]

3 CaO_2 + Fe^{2+}

Reactive oxygen chemistry and iron interactions complement sulfide control. The 2025 study reported a large cost advantage under its test conditions.[5]

4 OXIDATION + RE-FLOCCULATION

CaO_2 can open sludge structure; a downstream coagulant/flocculant then rebuilds separability. This sequence improved dewatering.[7]

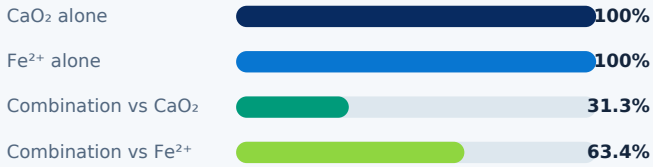
5 $FeCl_3$ + $Mg(OH)_2$

Iron captures sulfide while magnesium hydroxide offsets acidity and raises pH. A 2011 study achieved >95% removal with reduced dose.[6]

6 SOLIDS + P FIXATION

CaO_2 creates an alkaline calcium environment that can precipitate phosphate while disintegrating sludge.[9]

2025 CaO_2 + Fe^{2+} STUDY - RELATIVE COST



Read the savings correctly.

The 31.3% and 63.4% bars are relative chemical costs reported in one CaO_2-Fe^{2+} gravity-sewer study. They are evidence that synergy can change economics-not a universal price promise.

True synergy test: a combination should outperform the sum or cost-adjusted value of its individual components under equalized load and hydraulics.

APPLICATIONS

6. One sustained strategy across the treatment train

Sustained oxygen can be introduced upstream and evaluated through each downstream process. The treatment-train map connects each application point with the operational benefit and measurement needed to verify performance.

1 LIFT STATION + FORCE MAIN	2 HEADWORKS + EQ	3 BIOLOGICAL PROCESS	4 SOLIDS + BIOSOLIDS
• Raise ORP near the start of detention • Reduce SRB-driven sulfide formation • Target H_2S, methane and corrosion risk • Measure at the force-main discharge	• Reduce sulfide shock at turbulence points • Buffer septic influent • Lower headspace H_2S and odor peaks • Protect screens, channels and structures	• Reduce reduced-sulfur load entering aeration • Support process resilience-not replace aeration • Verify nitrification, denitrification and EBPR effects • Watch pH and mineral scaling	• Pair pretreatment with dewatering objectives • Track polymer, cake solids and hauling • Investigate phosphate fixation and odor control • Verify final biosolids compliance

Control point principle: dose where residence time begins, verify where turbulence releases gas, and measure the downstream process that captures the business value. A lift station is usually more informative than a generic “long collection run” image because it is a real, controllable injection and monitoring point.

DOWNSTREAM VALUE

7. Dewatering, digestion, phosphorus and biosolids

Downstream benefits depend on dose, sequencing and liquid-solids separation. The four evidence areas below show where solid oxidizers may add value and where verification is essential before a full-scale program is adopted.

DEWATERING

A 2016 study found an optimum 20 mg CaO_2/g TSS for pre-oxidation followed by chemical re-flocculation. The sequence matters: excessive disruption can create fines and hurt separation.[7]

ANAEROBIC DIGESTION

CaO_2 pretreatment increased methane production, VSS destruction and sludge reduction in biochemical methane-potential tests. Oxygen exposure, dose and feed solids must be optimized for anaerobic goals.[8]

PHOSPHORUS FIXATION

During waste-activated-sludge disintegration, calcium promoted phosphate precipitation. This may retain phosphorus in the solids phase, but it is not automatically “effluent P removal” unless liquid-solid separation follows.[9]

ODOR + BENEFICIAL USE

Preventing reduced-sulfur formation upstream can reduce odor carried into storage and transport. Finished biosolids still must meet pollutant, pathogen, vector-attraction, monitoring and management requirements.

REGULATORY REALITY

“Food grade” is not a biosolids permit.

A product’s raw-material grade or composition does not independently authorize land application. In the United States, the finished biosolids must meet 40 CFR Part 503 and applicable state/local requirements. Confirm current TDS/SDS, exact formulation, pollutant limits, pathogens, vector attraction reduction, management practices, monitoring, recordkeeping and reporting.[10]

Engineering implication: phosphorus removal, odor reduction and land-application compatibility are separate claims with separate measurements. Design the trial to prove each one.

BUSINESS CASE

8. Measure lifecycle value-not chemical price alone

Solid oxidizers can create value in several budgets at once. A defensible case normalizes every benefit to flow and pollutant load and subtracts equipment, maintenance and side-effect management.

CHEMICAL PROGRAM

Active chemical per pound sulfide controlled; residual duration; synergistic dose reduction; current vs proposed feed frequency.

OPERATIONS

Operator visits; tote or bag changes; calibration; spill containment; storage; emergency odor response.

ASSET PROTECTION

Headspace H_2S; corrosion coupons; coating life; concrete rehabilitation; metal replacement; confined-space exposure controls.

PROCESS ENERGY

Reduced-sulfur oxygen demand entering aeration; blower energy; mixing; pumping and any scaling penalty.

SOLIDS COST

Polymer; filtrate/centrate quality; cake solids; wet tons hauled; disposal or beneficial-use fees.

RESOURCE VALUE

Recovered carbon, methane, phosphorus retention or reduced greenhouse-gas formation-only when directly measured.

ANNUALIZED VALUE

Avoided chemical + avoided labor + avoided odor/corrosion cost + avoided solids cost + process/resource value
− incremental chemical − equipment − maintenance − side-effect management

Do not transfer published savings percentages into a proposal. The 2025 CaO_2-Fe^{2+} study and 2011 chemical-combination study prove that dose and mechanism interactions can change cost. A site budget must use current delivered pricing, actual feed equipment, real sulfide load and a defined performance boundary.

9. Pilot for performance, compatibility and value

A controlled pilot converts laboratory evidence into site-specific operating limits. Establish the baseline first, compare equalized conditions, optimize against a defined endpoint and verify downstream consequences before routine dosing.

1	BASELINE Map flow, detention, temperature, pH, ORP, dissolved sulfide and headspace H_2S across multiple hydraulic cycles. Add solids KPIs when relevant.
2	COMPARE Test untreated/current practice, three dose levels, and-when studying synergy-each component alone plus the combination under equalized load.
3	OPTIMIZE Choose the lowest dose that consistently meets a pre-agreed limit: H_2S percentile, sulfide at discharge, ORP floor, polymer dose or cake solids.
4	VERIFY DOWNSTREAM Confirm pH, alkalinity, mineral residuals, scaling, biological nutrient removal, centrate/filtrate, digester gas, final biosolids and worker safety.

Research-to-product translation

PeroxiMag™ and PeroxiCal™ translate the two solid-peroxide chemistries into deployable wastewater products. Each card keeps the product photograph, chemical identity, available form and research context within one frame. Product selection should follow the required release profile, available-oxygen target, feed method and site chemistry.

PeroxiMag™ / MgO_2 platform
Magnesium peroxide • available in powder or slurry
Closest direct research alignment: Chang 2007 solid-phase oxygen and Chang 2008 SRB-inhibition work.[1,2]

PeroxiCal™ / CaO_2 platform
Calcium peroxide • available in powder or slurry
Closest research alignment: sewer sulfide/methane, nitrate and iron synergy, sludge dewatering, digestion and phosphate fixation.[3-9]

The cited studies did not evaluate PeroxiMag or PeroxiCal by brand. Confirm current active concentration, formulation, application equipment, TDS/SDS and site chemistry before selection or dosing.

10. A release-profile decision

The deciding question is not simply which chemistry contains the most oxygen. It is whether the application requires a rapid reaction, a sustained oxygen reservoir or a validated combination of complementary mechanisms.

RAPID	SUSTAINED	SYNERGY
Use liquid H_2O_2 when the primary objective is immediate oxidation in a defined short contact zone.	**Use MgO_2 or CaO_2 when the objective includes time-distributed oxygen, ORP support, alkalinity and prevention.**	**Combine mechanisms only after a factorial test proves added performance or lower lifecycle cost.**

The research case is strongest where wastewater needs more than a momentary sulfide knockdown. Solid peroxide chemistry can connect upstream odor and corrosion control with downstream process resilience, solids performance and selected nutrient-management opportunities. The right program starts with the desired time profile and ends with measured site value.

Selected references

1. Chang, Y.-J., Chang, Y.-T., & Chen, H.-J. (2007). A method for controlling hydrogen sulfide in water by adding solid phase oxygen. Bioresource Technology 98, 478-483. doi:10.1016/j.biortech.2005.11.031
2. Chang, Y.-J., Chang, Y.-T., & Hung, C.-H. (2008). The use of magnesium peroxide for the inhibition of sulfate-reducing bacteria under anoxic conditions. JIMB 35, 1481-1491. doi:10.1007/s10295-008-0450-6
3. Guo, H., et al. (2023). Reduced sulfide and methane in rising main sewer via calcium peroxide dosing. Journal of Hazardous Materials 451, 131138. doi:10.1016/j.jhazmat.2023.131138
4. Zhang, Y., et al. (2023). Simultaneous use of nitrate and calcium peroxide to control sulfide and greenhouse gas emission in sewers. STOTEN 855, 158913. doi:10.1016/j.scitotenv.2022.158913
5. Zhang, Z., et al. (2025). Enhancing sulfide mitigation via the synergistic dosing of calcium peroxide and ferrous ions in gravity sewers. JHM 488, 137285. doi:10.1016/j.jhazmat.2025.137285
6. Othman, F., et al. (2011). Suppressing dissolved hydrogen sulfide in a sewer network using chemical methods. Scientific Research and Essays 6(17), 3601-3608. doi:10.5897/SRE10.897
7. Chen, Z., et al. (2016). Enhancement of waste activated sludge dewaterability using calcium peroxide pre-oxidation and chemical re-flocculation. Water Research 103, 170-181. doi:10.1016/j.watres.2016.07.018
8. Wei, W., et al. (2022). Calcium peroxide pre-treatment improved anaerobic digestion of primary sludge and co-digestion with WAS. STOTEN 828, 154404. doi:10.1016/j.scitotenv.2022.154404
9. Luo, H.-C., et al. (2022). Compared effects of “solid-based” hydrogen peroxide pretreatment on waste activated sludge. Chinese Chemical Letters 33(3), 1293-1297. doi:10.1016/j.cclet.2021.08.002
10. U.S. EPA. Sewage Sludge Laws and Regulations-40 CFR Part 503. epa.gov/biosolids
11. OCPE product technical literature. PeroxiMag™ magnesium-peroxide oxygen-release formulation; PeroxiCal™ engineered calcium-peroxide formulation. PeroxiCal™ provides ≥18% available oxygen with controlled release reported for more than 350 days under applicable product-test conditions.

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BIORESOURCE TECHNOLOGY

Short Communication

A method for controlling hydrogen sulfide in water by adding solid phase oxygen

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Abstract

This work evaluates the addition of solid phase oxygen, a magnesium peroxide (MgO_2) formulation manufactured by Regenesis (oxygen-releasing compounds, ORC^{TM}), to inhibit the production of hydrogen sulfide (H_2S) in an SRB-enriched environment. The initial rate of release of oxygen by the ORC was determined over a short period by adding sodium sulfite (Na_2SO_3), which was a novel approach developed for this study. The ability of ORCs to control H_2S by releasing oxygen was evaluated in a bench-scale column containing cultured sulfate reducing bacteria (SRB). After a series of batch tests, 0.4% ORC was found to be able to inhibit the formation of H_2S for more than 40 days. In comparison, the concentration of H_2S dropped from 20 mg S/L to 0.05 mg S/L immediately after 0.1% hydrogen peroxide (H_2O_2) was added, but began to recover just four days later. Thus, H_2O_2 does not seem to be able to inhibit the production of sulfide for an extended period of time. By providing long-term inhibition of the SRB population, ORC provides a good alternative means of controlling the production of H_2S in water.
Published by Elsevier Ltd.

Keywords: Hydrogen sulfide; Solid phase oxygen (SPO); Oxygen-releasing compounds (ORC); Sulfate reducing bacteria (SRB)

1. Introduction

Hydrogen sulfide (H_2S) is one of the main states of sulfur in the natural sulfur cycle. The dominant source of H_2S is the reduction of sulfate, the most common state in the natural aquatic system, by sulfate reducing bacteria (SRB) under anaerobic/heterotrophic conditions (Grossman and Desrocher, 2001). H_2S may cause several problems to both sewers and the water supply system such as odor and toxicity (Tomar and Abdullah, 1994). The corrosion caused by H_2S is also a serious challenge to environmental engineers, since 0.1–1 mg/L of sulfide in borehole water can cause well corrosion by depolarization and other mechanisms (Aller et al., 1991; Clarke, 1980).

Eliminating the growth of SRB is a primary approach to inhibit the generation of H_2S in groundwater. Disinfectant is generally added to water to kill SRB. However, the H_2S level recovers rapidly. The growth pattern of SRB population is consequently changed since the SRBs in suspension have been killed and from that point the immobilized SRB predominate in the groundwater system. Therefore, the SRB population becomes more resistant to disinfectant (Pope et al., 1984; Jones, 1996). In addition, many commercial disinfectants contain heavy metals and/or are toxic (Flick, 1987; Davidova et al., 2001), which makes their use inappropriate when applied to an observational groundwater system.

A commercial product that acts as an oxygen release compound (ORC^{TM}, Regensis, USA) is composed mainly of magnesium peroxide (MgO_2) and this was applied in this study. It can be reacted with water to release oxygen slowly to produce magnesium hydroxide ($Mg(OH)_2$). There are two major mechanisms by which ORC may be able to

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decrease sulfide concentration in water. One is the abiotic oxidation of sulfide to sulfate (Santegoeds et al., 1998; Sass et al., 2002), and the other is biotic inhibition of SRB by reducing the generation of sulfide (Sass et al., 2002; Khanal and Huang, 2003). Since ORC can release oxygen gradually over a long period of time (US EPA, 2000; Schmidtke et al., 1999; White et al., 1999), the addition of ORC would seem to be a suitable method of preventing H_2S production in soil and groundwater systems.

The purpose of this study is to evaluate the practicability of using ORC to prevent the generation of H_2S under anaerobic conditions for a long time period. The oxygen-releasing ability of ORC was investigated by reacting with sodium sulfite (Na_2SO_3) in water. The ability of ORC to inhibit the generation of H_2S over a long time period under SRB-enriched conditions was also evaluated using a bench-scale column test. Furthermore, ORC and hydrogen peroxide (H_2O_2) were compared in terms of their sustainability when controlling H_2S in water.

2. Methods

2.1. The oxygen release compound, ORC™

The ORC is a type of solid phase oxygen usually used during bioremediation. It is a solid compound with the potential to release oxygen when in contact with water. The ORC used in this study was purchased from Regenesis (San Clemente, California, USA). It is a formulation of magnesium peroxide (MgO_2) and phosphate ions produced by a patented process.

2.2. Evaluation of ORC to release oxygen

Different amounts of powdered ORC, from 0.5% to 2% (w/v), were added to 1 L polypropylene cylinders with a diameter of 7.5 cm and a height of 39 cm, which was filled with tap water. After the columns were purged with pure nitrogen gas, variations in the oxidation-reduction potential (ORP) and dissolved oxygen (DO) in these columns were measured simultaneously. These columns were sealed by a Parafilm® M barrier film to minimize oxygen entry from air (Fig. 1a). When the DO in the columns was almost at equilibrium, oxygen reductant (1.0 g of Na_2SO_3) was added to reduce the residual DO in the water. As the DO level recovered due to the release of oxygen by ORC, the initial release rate for oxygen was estimated over a short time interval.

2.3. SRB sludge inoculation

The original SRB was collected from a sewer system in ShenKeng, Taipei. Enriched synthesis medium containing KH_2PO_4 (8.5 mg), K_2HPO_4 (21.75 mg), $Na_2HPO_4 \cdot 7H_2O$ (33.4 mg), $CaCl_2 \cdot 2H_2O$ (27.5 mg), $MgSO_4 \cdot 7H_2O$ (22.5 mg), $FeCl_3 \cdot 6H_2O$ (0.25 mg), 5 mL of 50% sodium lactate (Sigma, USA) and 2.0 g of $Na_2SO_4 \cdot 10H_2O$ per liter of water was used to cultivate the SRB stock. The incubation substrate was refreshed once a week in a semi-batch manner. After incubation for a month, the SRB stock was ready for batch column inoculation.

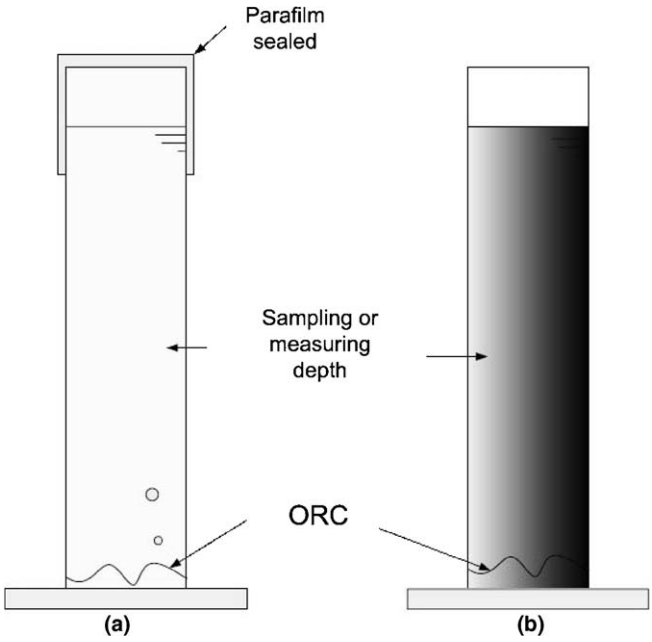

Fig. 1. The scheme for measuring variations in pH, DO and ORP in the (a) tap-water columns; and (b) SRB incubation columns.

2.4. Investigation of SRB-enriched column

The 0.8 L of substrate solution as described in the previous section, except for the addition of 3 mL of 50% sodium lactate and 0.86 g of sodium sulfate ($Na_2SO_4 \cdot 10H_2O$) to the medium, was poured into each of the six 1-L columns. Although the organic carbon concentration in the ground water is not high, excess carbon source (sodium lactate) and sulfate (sodium sulfate) were still added to each column to prevent interference due to the substrate exhaustion during batch column incubation. The SRB stock was then added to each column until a final optical density at 660 nm (OD_{660}) of 0.06 was reached. Before SRB inoculation, the columns were purged with ultra-pure nitrogen gas (Chinfeng, Taiwan) using a porous aerator. The incubation columns were not sealed in order to avoid the accumulation of either H_2S gas generated by the SRB or oxygen released by ORC (Fig. 1b). All columns were incubated at 25 °C for one month until the H_2S levels were relatively close to 15–20 mg S/L.

2.5. Sampling and analysis

Samples were taken periodically to determine the sulfide concentration, SRB activity and residual DO concentration in the systems. During the test process, the growth of SRB biomass was determined by OD_{660}. A glass electrode method was used to measure the ORP (Mettler Toledo,

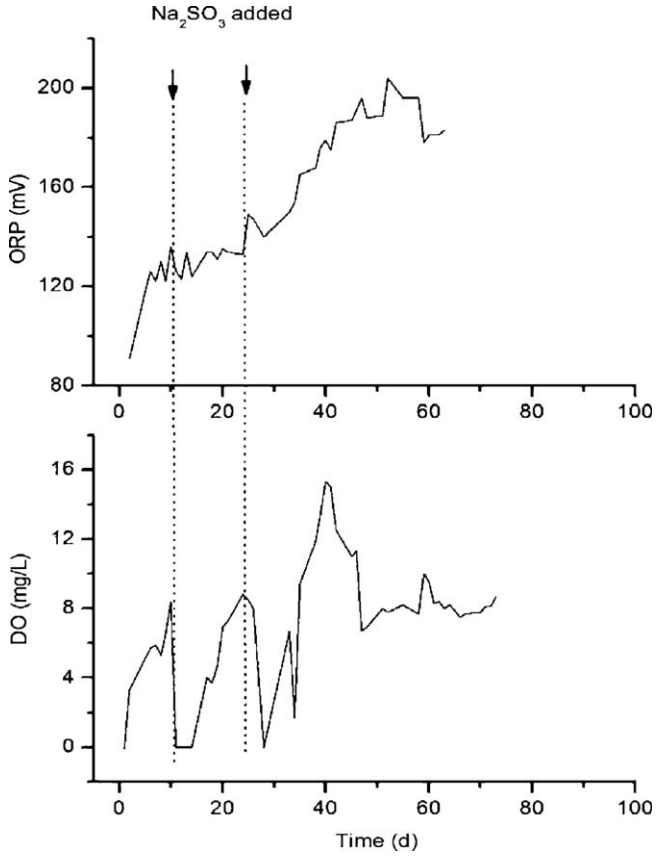

Fig. 2. DO and ORP versus time for 20 g of ORC added to 1 L tap water in the test column.

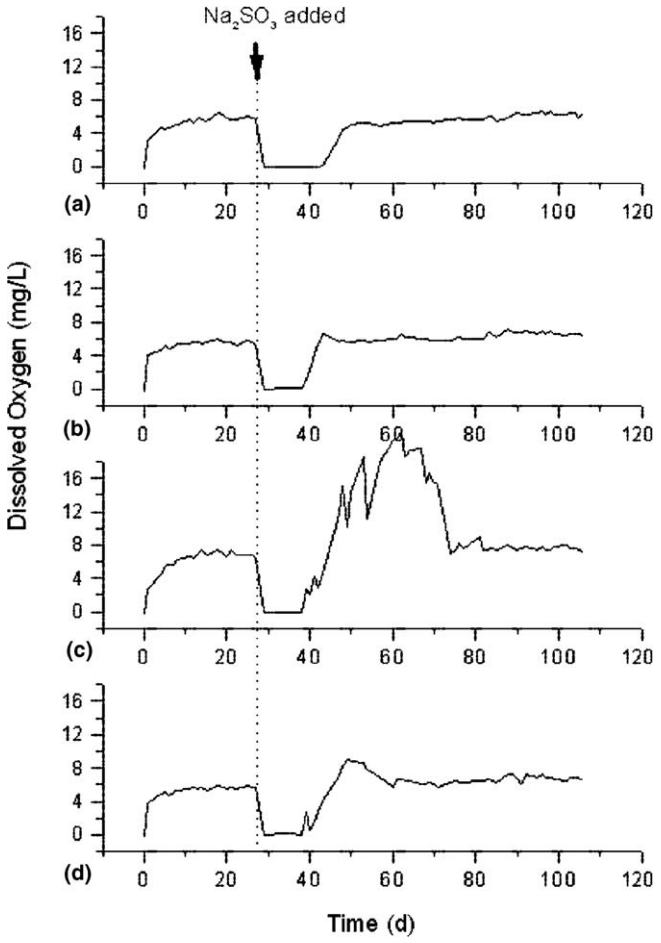

Fig. 3. Variation of DO against time under different ORC dosages and pre-mix ratios with water: (a) dosages = 0.5% (w/v), pre-mix ratio = 1:1; (b) dosages = 1% w/v, pre-mix ratio = 1:1; (c) dosages = 1% w/v, pre-mix ratio = 13:7; (d) dosages = 1% w/v, pre-mix ratio = 10:13.

Inc., Nederland) and DO (WTW, Weilheim, Germany). The concentration of sulfide and the OD_{660} were measured using a HACH DR2000 spectrometer (Loveland, Colorado, USA). The concentration of sulfate was measured using a Dionex DX-120 ion chromatograph analyzer (Sunnyvale, California, USA).

3. Results and discussion

3.1. ORC oxygen-releasing test

In Fig. 2, DO and ORP were plotted versus time for 20 g of ORC added to 1 L tap water in the test column. On the 10th day after adding ORC, 1.0 g of $Na_2SO_3 \cdot 10H_2O$ (a reductant of free oxygen) was added to the batch column. The DO level declined sharply to zero for a few days, and then the overall concentration of DO increased gradually due to the ORC-released oxygen, which consumed the Na_2SO_3. On the 26th day, another gram of Na_2SO_3 was added and the DO level again recovered rapidly. After reacting with Na_2SO_3, the DO level increased to 14 mg/L and then declined to approximately 8 mg/L, seemingly reaching an equilibrium level. The increase of ORP showed a similar tendency to the DO level further indicating the effect of ORC oxygen release ability in this experiment.

The variations of DO against time under different ORC dosages (0.5% for Fig. 3a and 1% for Fig. 3b) and different mixture conditions (at an ORC pre-mix ratio of 13:7 for Fig. 3c and 10:13 for Fig. 3d) are shown in Fig. 3. The DO levels were close to 6 mg/L in all columns for the first 26 days, which agrees with the observation obtained for 15 g of ORC dissolved in 250 mL water (Schmidtke et al., 1999). One gram of Na_2SO_3 was added to each column on the 27th day. Clearly, the column with a lower dose of ORC took more time to recover its DO level (Fig. 3a). Thus, the effects of various pre-mix ratios were ignored in this study.

The initial rates of oxygen releasing by ORC were estimated by calculating the time needed for the oxygen to recover to the equilibrium point in both Figs. 2 and 3. The test columns were never disturbed except for measuring the quality of the water. Accordingly, the oxygen releasing rates were calculated to be 0.120, 0.006, 0.009, 0.008 and 0.008 g of oxygen per day from Figs. 2 and 3a, b, c and d, respectively. Therefore, the initial oxygen-releasing rates are clearly determined by the amount of ORC rather than the pre-mix ratios of ORC with water.

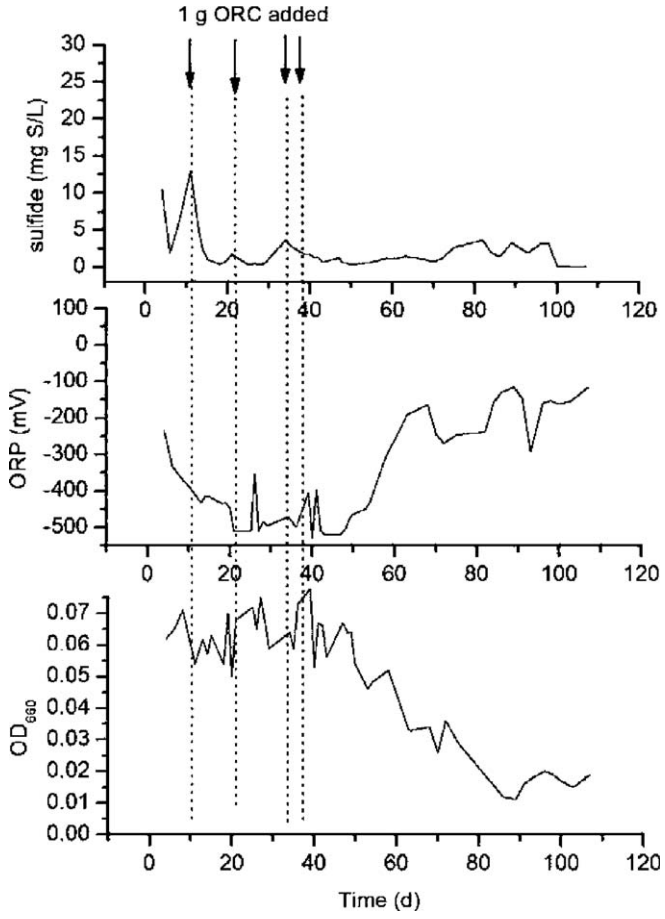

Fig. 4. Variation of sulfide, ORP and OD_{660} values with incubation time. The arrow points indicate the time of ORC addition (1 g) to the SRB column (a total of 4 g of ORC was added).

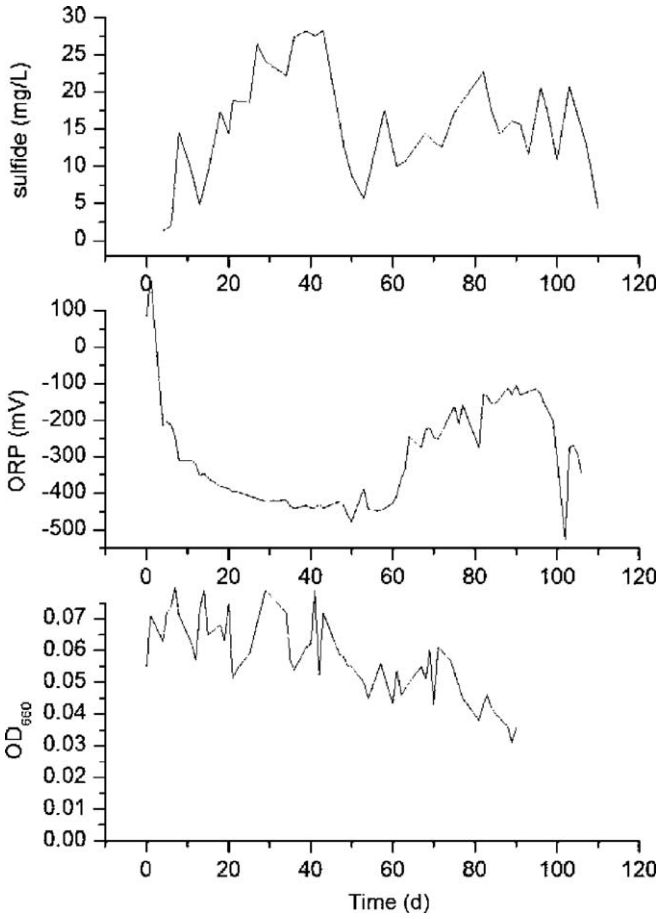

Fig. 5. Variation of sulfide, ORP and OD_{660} values in the control SRB-enriched column.

3.2. SRB-enriched columns test

After its oxygen-releasing rate was evaluated initially, ORC was added to two SBR-enriched columns to carry out further investigations. The results are shown in Fig. 4. The characteristics of both sustainable and slow-releasing oxygen were evaluated. The amount of ORC added to the incubated columns was 1 g (0.1%, w/v) on each occasion. It was repeated until the sulfide concentration was clearly controlled. Based on Fig. 4, it appears that the sulfide concentration reached 12.95 mg/L on the 11th days, and 1 g of ORC was added on the 11th, 20th, 35th and 36th days to control the generation of sulfide. The accumulated weight of ORC added was 0.4% of the volume of the column. On the 50th day, the ORP increased and OD_{660} value of the SRB culture declined rapidly (Fig. 4).

The sulfide concentration was maintained below 4 mg S/L, during the first 50 days of incubation in which the ORC was added in the column (Fig. 4). The concentrations of sulfide were approximately 10–20 mg/L at the same time points in the SRB-enriched columns that acted as controls (shown as Fig. 5). The sulfide is produced by the SRB under anaerobic conditions. A gradually dosage of 0.4% (W/V) ORC in this study was effective at reducing the sulfide concentration to an acceptable outcome.

In Fig. 4, once the ORP exceeded −300 mV, the OD values decreased considerably and the sulfide concentration never recovered thereafter, perhaps because of SRB death (Sass et al., 2002) or inhibition due to the released oxygen. Khanal and Huang (2003) also found that sulfide was removed when ORP elevated from −280 mV to −230 mV.

The columns to which ORC were added and the control SRB-enriched columns exhibited similar characteristics. The ORP values increased on approximately the 50th day and 60th day in both the ORC-added columns (Fig. 4) and the control columns (Fig. 5). The oxygen released by ORC clearly promoted an increase in ORP values in this study. Theoretically, the ORP should decline as SRB incubation time increases (Iverson, 2001; Lyew and Sheppard, 2001). However, the opposite results were obtained in this study. In terms of the biotic aspects, the lower ORP may mean that an anoxic environment was created and there was higher growth of the SRB population in the culture. In this study, the addition of ORC effectively and significantly inhibited the SRB growth. This could be because the added ORC promotes the utilization of substrate (sodium lactate) by the aerobic or facultative microorganisms. When the

substrate was used up, the growth of SRB was inhibited and the ORP increased simultaneously.

When the substrate was limited, the oxygen seemed to have a significant effect on the ORP due to the open incubation of the test columns (Fig. 1b). Previous studies support the possibility that the SRB can produce enough sulfide to maintain an anaerobic condition (Cypionka, 2000; Lemos et al., 2001). It is believed that the increase in ORP value after 60th day in the control column (Fig. 5) was due to an inhibition of sulfate reducing reaction. In the control column, ORC was not added. There are two possible reasons as to why there was a loss of the sulfate reducing reaction in the water. One is the oxygen from the atmosphere. The other is consumption of the organic carbon source. However, notwithstanding whether either atmospheric oxygen or the carbon source was involved, the addition of ORC could actually promote an increase in ORP at an earlier stage. It is clear that the addition of ORC is able to inhibit the activity of SRB in the water column system used in this study.

3.3. Hydrogen peroxide addition

Recently, several researchers have used nitrate (Nemati et al., 2001a; Davidova et al., 2001), nitrite (Nemati et al., 2001b; Greene et al., 2003) or hydrogen peroxide (H_2O_2) (Tomar and Abdullah, 1994) to control the production of H_2S by SRB in water. Except for H_2O_2, these inhibitors are hazardous to public health and so it is not feasible to apply these to observational wells that are directly connected to underground aquifers. The variation in several parameters with time following the addition of H_2O_2 is shown in Fig. 6. The column to which H_2O_2 was added showed a faster but poorly sustainable inhibition of the yield of sulfide compared to the columns to which ORC had been added. The concentration of sulfide dropped from 20 mg S/L to 0.05 mg S/L immediately after 0.1% (w/v) H_2O_2 was added on the 36th day (Fig. 6) and began to recover after only four days, reaching 10 mg S/L within 10 days. Theoretically, 1.25 g H_2O_2 is required to oxidize 1 g of sulfide (Tomar and Abdullah, 1994), so the amount of H_2O_2 added should be in excess of that needed to oxidize sulfide completely throughout the whole column (20 mg). However, the residual H_2O_2 did not seem to be able to sustain the inhibition of sulfide production in this study for any length of time.

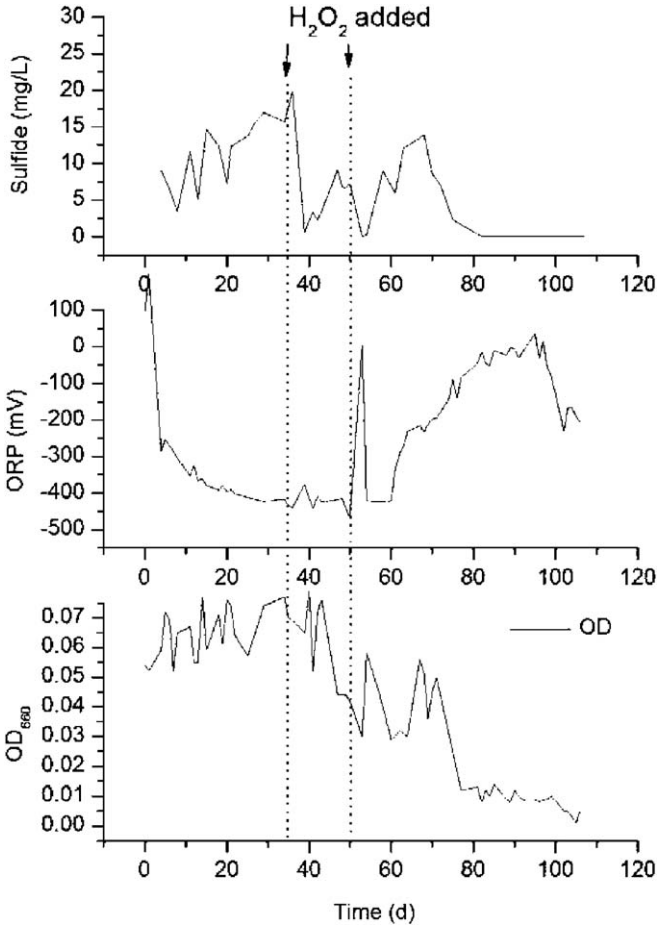

Fig. 6. Variation of sulfide, ORP and OD_{660} values with incubation time. The arrow points indicate the time of ORC addition (1 g) to the SRB column (a total of 2 g of H_2O_2 was added).

4. Conclusions

The initial oxygen-releasing rates of the ORC were determined over a short time period by a new approach developed in this study. The oxygen-release rates were clearly determined by the amount of ORC rather than the pre-mix ratios of ORC with water. Using a series of SRB-enriched columns tests, 0.4% of ORC was found to inhibit the formation of sulfide for more than 60 days. The results of this study show that the generation of H_2S in the water was inhibited and this is accompanied by an inhibition of SRB growth. Based on the results, we proposed that the addition of ORC to the water can be used to augment the oxygen environment. This environment will inhibit the growth of the SRB and therefore also inhibit sulfide generation in the water. By inhibiting SRBs, ORC provides a good alternative for controlling H_2S in water. This study demonstrated that the addition of ORC to control biogenic hydrogen sulfide seems to be practical. With ORC's characteristics of persistence, harmlessness and effectiveness, the application of ORC for in situ corrosion control in observational wells is worthy of further research.

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References

Aller, L., Bennett, T.W., Hackett, G., Petty, R.J., Lehr, J.H., Sedoris, H., Nielson, D.M., Denne, J.E., 1991. Handbook of suggested practices for the design and installation of ground-water monitoring wells. EPA160014-891034.

Clarke, F.E., 1980. Corrosion and encrustation in water wells. Food and Agriculture organization of the United Nations.

Cypionka, H., 2000. Oxygen respiration by Desulfovibrio species. Annu. Rev. Microbiol. 54, 827–848.

Davidova, I., Hicks, M.S., Fedorak, P.M., Suflita, J.M., 2001. The influence of nitrate on microbial process in oil industry production waters. J. Ind. Microbiol. Biotech. 27, 80–86.

Flick, E.W., 1987. Corrosion Inhibitors: An Industrial Guide. Noyes Publication, NJ, US.

Greene, E.A., Hubert, C., Nemati, M., Jenneman, G.E., Voordouw, G., 2003. Nitrite reductase activity of sulphate-reducing bacteria prevents their inhibition by nitrate-reducing, sulphide-oxidizing bacteria. Environ. Microbiol. 5, 607–617.

Grossman, E.L., Desrocher, S., 2001. Microbial sulfur cycling in terrestrial subsurface environments. In: Fredrickson, J.K., Fletcher, M. (Eds.), Subsurface Microbiology and Biogeochemistry. John Wiley & Sons, Inc., London, pp. 219–248.

Iverson, W.P., 2001. Research on the mechanisms of anaerobic corrosion. Int. Biodeteriorat. Biodegrad. 47, 63–70.

Jones, D.A., 1996. Principles and Prevention of Corrosion. Prentice Hall, NJ, USA.

Khanal, S.K., Huang, J., 2003. ORP-based oxygenation for sulfide control in anaerobic treatment of high-sulfate wastewater. Water Res. 37, 2053–2062.

Lemos, R.S., Gomes, C.M., Santana, M., LeGall, J., Xavier, A.V., Teixeira, M., 2001. The 'strict' anaerobe Desulfovibrio gigas contains a membrane-bound oxygen-reducing respiratory chain. FEBS Lett. 496, 40–43.

Lyew, D., Sheppard, J., 2001. Use of conductivity to monitor the treatment of acid mine drainage by sulphate-reducing bacteria. Water Res. 35, 2081–2086.

Nemati, M., Jenneman, G.E., Voordouw, G., 2001a. Mechanistic study of microbial control of hydrogen sulfide production in oil reservoirs. Biotech. Bioeng. 74, 424–434.

Nemati, M., Mazutinec, T.J., Jenneman, G.E., Voordouw, G., 2001b. Control of biogenic H_2S production with nitrite and molybdate. J. Ind. Microbiol. Biotech. 26, 350–355.

Pope, D.H., Duquette, D., Wayner Jr., P.C., Johannes, A.H., 1984. Microbiologically influenced corrosion: a state-of-the-art review. Materials Technology Institute of the Chemical Process Industries, Inc., MO, USA.

Santegoeds, C.M., Ferdelman, T.G., Muyzer, G., de Beer, D., 1998. Structural and functional dynamics of sulfate-reducing populations in bacterial biofilms. Appl. Environ. Microbiol. 64, 3731–3739.

Sass, A.M., Eschemann, A., Kühl, M., Thar, R., Sass, H., Cypionka, H., 2002. Growth and chemosensory behavior of sulfate-reducing bacteria in oxygen-sulfide gradients. FEMS Microbiol. Ecol. 40, 47–54.

Schmidtke, T., White, D., Woolard, C., 1999. Oxygen release kinetics from solid phase oxygen in Arctic Alaska. J. Hazard. Mater. B 64, 157–165.

Tomar, M., Abdullah, T., 1994. Evaluation of chemicals to control the generation of malodorous hydrogen-sulfide in waste-water. Water Res. 28, 2545–2552.

US EPA, 2000. Engineered approaches to in situ bioremediation of chlorinated solvents: fundamentals and field applications. US EPA, Office of Solid Waste and Emergency Response, Technology Innovation Office, EPA 542-R-00-008, Washington, DC.

White, D., Schmidtke, T., Woolard, C., 1999. Laboratory model of a petroleum migration barrier in Arctic Alaska. J. Hazard. Mater. B 67, 313–323.