

Title

Evaluating UV/H₂O₂ Processes for Methyl *tert*-Butyl Ether (MtBE) and tertiary Butyl Alcohol (tBA) Removal from Drinking Water Source: Effect of Pretreatment Options and Light Sources

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Abstract

The Charnock wellfield in the City of Santa Monica (COSM) are contaminated with approximately 300 µg/L of methyl *tert*-butyl ether (MtBE) and 30 µg/L of tertiary butyl alcohol (tBA). In order to reduce MtBE and tBA below the targeted level of 2.5 µg/L of MtBE and 6.0 µg/L of tBA, respectively, an advanced oxidation process using H₂O₂ with UV irradiation (UV/H₂O₂) was selected. Kinetic models were used to evaluate the removal efficiency of the UV/H₂O₂ technologies with different pretreatment options. In addition, two commercially available UV light sources, i.e., low pressure, high intensity lamps (LPUV) and medium pressure, high intensity lamps (MPUV), were evaluated. Based on the analysis of the raw water quality, the following pretreatment alternatives were considered to improve the performance of the UV/H₂O₂ AOP: 1) existing ion exchange softening with seawater regeneration (NaIX); 2) ion exchange softening via pellet reactors (Pellet Softening); 3) weak acid ion exchange (WAIX); and 4) high pH lime softening followed by reverse osmosis (RO). The presence or absence of a dealkalization step to reduce bicarbonate and carbonate alkalinity prior to the UV/H₂O₂

AOP was also evaluated for each pretreatment possibility. Therefore, a total of 16 alternatives were assessed (LPUV vs MPUV for each of four pretreatment alternatives (NaIX, Pellet Softening, WAIX, RO), with or without Dealkalization).

Model predictions demonstrated that the pretreatment alternatives and type of UV lamp (LPUV or MPUV) significantly affected the UV/H₂O₂ performance, i.e., the required number of photo-reactors and power, hence both capital and operating costs. The pretreatment alternative of NaIX with dealkalization was shown to be the most cost effective. With the NaIX pretreatment and 10mg/L H₂O₂ dosage, calculated electrical energy per order (EE/O) values for treating MtBE and tBA to meet the treatment objectives using LPUV/H₂O₂ AOP technology are 0.77 kWh-kgal/order and 3.0 kWh-kgal/order, respectively; whereas, MPUV/H₂O₂ AOP technology resulted in EE/O values for MtBE and tBA of 4.6 and 15 kWh-kgal/order.

Key Words (6)

UV/H₂O₂ process, hydroxyl radical, MtBE, tBA, EE/O, H₂O₂ dose and residual concentration

Introduction

In 1995, the City of Santa Monica (COSM) discovered the gasoline additive methyl tertiary-butyl ether (MtBE) in drinking water supply wells at its Charnock Wellfield and shut down the affected wells. A lawsuit was filed by COSM against the potentially responsible parties (PRPs) for redress of the contaminated drinking water wells. This lawsuit was settled in 2003 and required the PRPs to pay for the design, construction,

operation and maintenance of a water treatment plant to treat the contaminated groundwater to potable water quality standards. Trussell Technologies was retained in 2005 to appraise the value of the Settlement.

According to the Settlement Agreement, the water treatment plant must be designed for a peak flow rate of 7,000 gpm (10.1 MGD) to treat influent concentrations of 300 µg/L of methyl *tert*-butyl ether (MtBE) and 30 µg/L of tertiary butyl alcohol (tBA). In light of California Department of Health Services (CDHS) regulations and policy guidance, treatment targets for MtBE and tBA were established as: MtBE ≤ 2.5 µg/L and tBA ≤ 6 µg/L.

Because MtBE and tBA, especially tBA, are difficult to remove using adsorption or air stripping (Sutherland *et al.*, 2005; Yu *et al.*, 2005; Erdem-Şenatalar *et al.*, 2004; Sutherland *et al.*, 2004; Carter *et al.*, 2000; Federal Register, 1991), these technologies were eliminated from consideration to reduce MtBE and tBA at the required levels. The advanced oxidation processes (AOPs) ozone/hydrogen peroxide (O₃/H₂O₂) and ultraviolet light/hydrogen peroxide (UV/H₂O₂) were considered because they represent an attractive possibility as the primary technologies for the removal of MtBE and tBA from the Charnock wellfield (Chang *et al.*, 2000; Wagler and Malley, Jr., 1994).

The raw water quality of the Charnock wellfield is listed in Table 1. The concentration of bromide is as high as 0.9 mg/L. This makes O₃/H₂O₂ process less attractive due to the potential formation of bromate, which is classified by the U.S. EPA as a “probable human carcinogen” and has a current drinking water limit of 10 µg/L (National Institutes of Health, 2005). Although there are methods available to control bromate formation in O₃/H₂O₂ process (Neemann, *et al.*, 2004; Buffle *et al.*, 2004;

Ozekin *et al.*, 1998; Westerhoff *et al.*, 1998; von Gunten and Hoigné, 1994), it would be cost prohibitive and difficult to consistently control the bromate under regulation at the high bromide concentration. Therefore, UV/H₂O₂ was chosen for MtBE and tBA treatment. However, the presence of NOM, high alkalinity, and certain minerals, specifically iron, manganese, and hardness in the raw Charnock water are undesirable for UV/H₂O₂ process.

(Table 1 goes here)

Removal of MtBE using UV/H₂O₂ has been investigated recently. Carter *et al.* (2000) examined the EE/O of removal of MtBE during the UV/H₂O₂ process. They found that the EE/O values varied in the range from 0.2 to 7.5 kWh/m³/order depending on the initial concentrations of MtBE and the H₂O₂ dosage. Sutherland *et al.* (2004) reported the electrical energy per order (EE/O) of MtBE range from 0.37 to 65.1 kWh/kgal/order for 5 different groundwaters. The effect of natural organic matter (NOM) was not specifically discussed. These results, as well as the factors discussed below, imply that the design of UV/H₂O₂ process requires careful consideration of the raw water quality and the evaluation of various pretreatment options.

METHODS

Factors Affecting the UV/H₂O₂ Process The following factors affect the performance of UV/H₂O₂ by interfering with the production of hydroxyl radicals or scavenging them: (1) presence of carbonate species; (2) presence of natural organic matter (NOM); (3) pH; (4) presence of reduced metal ions (iron and manganese); (5) reactivity of the target compound, designated *R*, with hydroxyl radical (HO•); (6) UV lamp technology; (7) and hydrogen peroxide dosage.

Presence of Carbonate Species Bicarbonate and carbonate ions scavenge HO• and their presence can greatly reduce the destruction rate of organics in AOPs (Glaze and Kang, 1988). While the HO• rate constants for bicarbonate and carbonate species are an order of magnitude lower than those of many organics, the concentration of bicarbonate and carbonate ions are often several orders of magnitude higher than the concentration of the target compound, making the presence of alkalinity an important factor influencing any AOPs, including UV/H₂O₂. Reactions between HO• and carbonate species, i.e., HCO₃⁻ and CO₃²⁻ are shown in Equations 1 and 2, respectively. The distribution of the consumption of hydroxyl radicals among the reactant species is a measure of how efficiently AOPs perform. The fraction of HO• consumed in the oxidation of a target compound, *R*, in the presence of carbonate species, is shown in Equation 3 (Glaze and Kang, 1987).



$$\eta_R = \frac{k_R C_R}{k_R C_R + k_{\text{HCO}_3^-} C_{\text{HCO}_3^-} + k_{\text{CO}_3^{2-}} C_{\text{CO}_3^{2-}}} \quad (3)$$

where η_R = target organics reaction rate with HO• divided by total reaction rate of HO•

with *R* and carbonate species

k = second order HO• rate constant, L/mole/s

C = concentration, mole/L

When both are present at the equal concentration, the presence of carbonate ion is more detrimental than that of bicarbonate ion because its reaction rate with HO• is approximately 45 times greater than that of bicarbonate. Therefore, in terms of reducing

the impact of carbonate species, it is desirable to operate at lower pH because bicarbonate species will prevail at lower pH compared to carbonate ($pK_{a2} = 10.3$ at $25\text{ }^{\circ}\text{C}$ for $\text{HCO}_3^-/\text{CO}_3^{2-}$ equilibrium). For example, below a pH of about 8.3, there is no significant carbonate ion (CO_3^{2-}) present in the water. Also, if pH is lowered by adding acid to a pH of about 4.3 ($pK_{a1} = 5.3$ at $25\text{ }^{\circ}\text{C}$ for $\text{H}_2\text{CO}_3^*/\text{HCO}_3^-$ equilibrium), the alkalinity is completely converted to aqueous carbon dioxide (H_2CO_3^*) and it will not affect AOP performance. (However, one must consider the impact on the total dissolved solids and this is discussed later.) The pH affects the system in other ways, as discussed below, and all pH impacts on the AOP performance must be carefully considered in deciding an appropriate design.

Presence of NOM NOM present in the background water matrix can reduce the reaction rate of the target compound with $\text{HO}\cdot$ by scavenging hydroxyl radicals in the same manner as scavenging by carbonate species, as discussed above (Crittenden *et al.*, 2005). The $\text{HO}\cdot$ rate constant for NOM, k_{NOM} , is on the order of 3×10^8 to 4.5×10^8 L/mole NOM carbon•s based on a study of 17 water sources (Westerhoff *et al.*, 1999). An expression for the fraction of $\text{HO}\cdot$ consumed in the oxidation of a target compound, R , in the presence of NOM (η_R) is shown in Equation 4. In general, the effect of NOM on reducing the efficiency of AOPs is greater than the effect of carbonate species.

$$\eta_R = \frac{k_R C_R}{k_R C_R + k_{\text{NOM}} C_{\text{DOC}}} \quad (4)$$

where η_R = target organics reaction rate with $\text{HO}\cdot$ divided by total reaction rate of $\text{HO}\cdot$

with R and NOM

C_{DOC} = concentration of NOM, mole NOM C/L

In the UV/H₂O₂ process, NOM present in the water can also absorb UV light before UV irradiation into H₂O₂ is able to form hydroxyl radicals. This reduces the amount of UV light available in support of the desired reactions in the UV/H₂O₂ process. This issue is discussed further in the section on the UV light transmission below.

Absorption of UV Light by NOM and Determination of the HO• Rate Constant for NOM The extinction coefficient for NOM varies widely and is site specific. However, the specific UV absorption ratio at 254 nm (SUVA) is widely available because it is used in estimating the potential for the production of the disinfection byproducts (DBPs) (Crittenden *et al.*, 2005). The SUVA (L/mg carbon•m) is equal to the extinction coefficient for NOM at 254 nm (L/mg carbon•cm) times 100 cm/m. Ranges for the SUVA values for NOM and extinction coefficients for NOM at 254 nm have been reported to be between 1.3 to 10.7 of the SUVA (L/mg carbon•m), 0.013 to 0.107 of the ϵ_{NOM} (L/mg carbon•cm), respectively (Bolton, 1999).

The following expression, which is based on a linear regression of data for 17 water sources, can be used to determine HO• rate constant for NOM when the SUVA is known (Westerhoff *et al.*, 1999):

$$k_{NOM} \left(\frac{L}{mole\ carbon \cdot s} \right) = \left[0.52 \times SUVA \left(\frac{L}{mg\ carbon \cdot m} \right) + 2.0 \right] \times 10^8 \quad (5)$$

pH The pH affects UV/H₂O₂ process in several ways and the impacts of pH need to be carefully balanced in the process design. The pH dictates the amount of bicarbonate or carbonate species that are present, the effect of which was discussed above. The pH determines how much HO₂⁻ (pK_a of H₂O₂=11.6) is present, which is important when H₂O₂ is used for AOPs (i.e. O₃/H₂O₂, UV/H₂O₂). HO₂⁻ absorbs UV light more effectively

than H₂O₂, which means AOPs that involve H₂O₂ and UV light may be more effective at higher pH. Finally, the pH affects the charge on the target organics if they are weak bases or weak acids. For some chemicals, the ionic form has a rate constant one or two orders of magnitude higher than the molecular form. Thus, higher pH increases the degradation rate. However, in the removal of MtBE and tBA, the dissociation of those compounds is negligible, so that the effect of pH is not important.

Presence of Reduced Metal Ions (Iron and Manganese) Reduced metal ions, such as iron, Fe(II), and manganese, Mn(II), can scavenge hydroxyl radicals in a similar manner to the HO• scavenging discussed above for the carbonate species and NOM (Crittenden *et al.*, 2005). An expression for the fraction of HO• consumed in the oxidation of a target compound, *R*, in the presence of reduced metal ions (η_R) is shown in Equation 6:

$$\eta_R = \frac{k_R C_R}{k_R C_R + k_{Fe(II)} C_{Fe(II)} + k_{Mn(II)} C_{Mn(II)}} \quad (6)$$

where η_R = target organics reaction rate with HO• divided by total reaction rate of HO•

with *R*, iron and manganese, dimensionless

$$k_{Fe(II)} = 2.3 \times 10^8 \text{ L/mole} \cdot \text{s (Buxton } et al., 1988)$$

$$k_{Mn(II)} = 1.4 \times 10^8 \text{ L/mole} \cdot \text{s (Buxton } et al., 1988)$$

In AOPs that involve UV light, both Fe(II) and Fe(III) will absorb UV light and reduce the effectiveness of AOPs for removal of the target compound. The impacts of Fe(II) and

Mn(II) on the UV/H₂O₂ are discussed in more detail in the section of the UV light transmission below.

Reactivity of the Target compound, R, with HO• The second order HO• rate constant for the target compound determines AOP performance (Crittenden *et al.*, 2005). The second order reaction rate constants of HO• for MtBE and tBA are: $k_{MTBE} = 1.6 \times 10^9$ L/mole · s (Eibenberger, 1980; Buxton *et al.*, 1988), $k_{TBA} = 6.0 \times 10^8$ L/mole · s (Buxton *et al.*, 1988), respectively. This indicates that MtBE is easier to destroy than tBA.

UV Lamp Technology Two types of lamps were considered for removal of MtBE and tBA from the Charnock wells: low pressure, high intensity (LPUV) lamps and medium pressure, high intensity (MPUV) lamps. Both are in use at the full-scale in California. LPUV lamps emit all their energy at a wavelength of 254 nm; whereas, MPUV lamps emit their energy in a wide range of the UV spectrum between 200 and 400 nm.

LPUV lamps generate light more efficiently than MPUV lamps. LPUV lamps have a UV efficiency on the order of 30 to 40 percent, as compared to 10 to 15 percent for MPUV lamps. The UV efficiency, which can be expressed as a percentage or a decimal, is defined as the amount of lamp power input in Watts converted into Watts of light emitted in the range of 200 to 300 nm. This means that it takes a greater amount of power to generate the same amount of light intensity for MPUV lamps as compared to LPUV lamps. On the other hand, MPUV lamps can operate at a higher power input; consequently, less lamps are needed for a MPUV reactor which reduces maintenance problems. However, the overall power requirements for a MPUV reactor are greater for a

given amount of destruction. Another disadvantage of MPUV lamps is that the ability of UV light to generate hydroxyl radicals goes down above the wavelength of 254 nm because the extinction coefficient of H₂O₂ is lower relative to other species, such as NOM, iron, and nitrate when the wavelength is greater than 254 nm. In addition, extinction of UV is also a problem for wavelengths less than 254 nm, because even pure water begins to absorb a significant amount of UV light.

The photons entering the reactor per unit volume and time, P_{U-V} (einsteins/L-s), can be theoretically determined from the following expression:

$$P_{U-V} = \frac{P \times \eta}{N_{av} \times V \times h \nu} \quad (7)$$

where P = lamp power, W

η = UV efficiency expressed as a fraction, dimensionless

N_{av} = Avogadro's number, 6.023×10^{23} molecules/mole

V = reactor volume, L

h = Planck's constant, 6.62×10^{-34} J•s

ν = frequency of light = c / λ , s⁻¹

c = speed of light, 3.00×10^8 m/s

λ = wavelength of light, m

The P_{U-V} which is determined from Equation 7 represents the highest possible light intensity per unit volume but actual reactor performance can not achieve this level because precipitate forms on the lamp sleeve and reactor walls and reflects light, making it unavailable for absorption and the lamp efficiency decreases with time.

In order to ensure the low cost and high efficiency of the UV/H₂O₂ process, it is important to choose an appropriate light source and use pretreatment processes to

eliminate the potential negative factors described above. According to the raw water quality and existing facility at the local water treatment plant the following processes were selected as effective pretreatment alternatives: (1) an ion exchange softening system with seawater regeneration (NaIX); (2) softening using pellet reactors (Pellet Softening); (3) weak acid ion exchange process (WAIX), and (4) high pH lime softening followed by reverse osmosis (RO). Dealkalization is considered with all the alternatives to minimize the presence of alkalinity in the AOP.

To find the most efficient treatment processes and size the UV/H₂O₂ system, a kinetic model was used to predict the removal efficiency of a LPUV and a MPUV system with the different pretreatment alternatives above.

Model of the UV Hydrogen Peroxide Process The performance of the UV/H₂O₂ system was predicted using the AOP model entitled Advanced Oxidation Process Simulation Software, which is referred to as AdOx™ (Crittenden *et. al.*, 1999; Li *et. al.*, 2000). AdOx™ is a kinetic model that includes known elementary chemical and photochemical reactions. AdOx™ provides a more accurate representation of real systems than many other AOP models because it does not make simplifying assumptions common in other approaches, including the pseudo-steady-state assumption and constant pH. It is able to predict organic contaminant destruction in varying water quality and operational conditions. The model can simulate the fate of up to 10 target compounds in a UV system containing up to 100 wavelengths and the effects of hydroxyl radical scavengers, such as NOM, inorganic metals, and carbonate species. Detail of the AdOx™ model was elaborated elsewhere (Li, 2003; Crittenden, 1999). A simplified description is discussed below and it includes the rate expressions corresponding to the

elementary reactions solved in the model, a description of the system of ordinary differential equations solved simultaneously by the model for a tanks-in-series (TIS), and assumptions and calculations that are needed for this example.

Elementary Reactions and Rate Expressions The important elementary reactions for the UV/H₂O₂ process are presented in Table 2.

(Table 2 goes here)

Based on the elementary reactions, the rate expressions can be written in Table3 (note that there are two target compounds, R, corresponding to elementary reaction 13, MtBE and tBA, and the rate expressions below will be written in terms of the target compounds)

(Table 3 goes here)

The AOP model, AdOxTM, accounts for the reaction rate expressions shown above in a manner demonstrated below.

Model Equations The application of AdOxTM to predict the performance of the LPUV and MPUV reactors will utilize a series of CMFRs to describe the mixing condition. The mass balance for a generic species, “A,” in a single CMFR yields the following ordinary differential equation (ODE):

$$\frac{dC_A}{dt} = \frac{1}{\tau}(C_{A0} - C_A) + r_A \quad (33)$$

For the tanks-in-series model, the general form of the ODE to be solved is represented by:

$$\frac{dC_{A,1}}{dt} = \frac{1}{\tau_1}(C_{A0} - C_{A,1}) + r_{A,1} \quad \text{for tank 1} \quad (34)$$

$$\frac{dC_{A,j}}{dt} = \frac{1}{\tau_j}(C_{A,j-1} - C_{A,j}) + r_{A,j} \quad \text{for tanks 2 through n} \quad (35)$$

The generic species, “A,” represents each of the species shown in Equations 21 to 27. The Gear algorithm, a backward difference approximation method, is used to solve the stiff system of ODEs (Li, 2003; Crittenden *et al.*, 1999; Hu, 1999).

Assumptions The assumptions employed in AdOx™ from the Charnock wellfield are:

- MtBE and tBA are the only target compounds
- Nitrate, ferrous iron and NOM are the only substances that interfere with the absorption of UV light by H₂O₂ (although measured values for the extinction of UV light were used by attributing the absorption of UV light not attributed to nitrate and iron to NOM).
- Direct photolysis of MtBE and tBA is negligible.
- Ferrous iron, NOM, carbonate and bicarbonate are the only HO• scavengers.
- The effective UV irradiation range of medium pressure lamps is from wavelengths of 200nm to 300nm because H₂O₂ can only absorb light in this range.
- Low pressure lamps only emit light at 254nm.
- The decrease of UV irradiation due to scaling and bulb aging was accounted by assuming that the photon flux is 70 % of what is emitted according to the manufacturer’s specifications.
- All UV irradiation is absorbed by the water matrix.

The AdOx™ model was used to size the LPUV and MPUV systems to treat MtBE and tBA in the Charnock wellfield for the raw water and eight pretreatment alternatives

Influent Water Quality Table 4 summarizes the key water quality parameters of the influent into the UV/H₂O₂ process after the eight pretreatment alternatives.

(Table 4 goes here)

UV Absorption and Reactivity of NOM Table 5 listed below shows the UV absorbance of the different species in the water and the calculated fraction of light absorbed by H₂O₂. Assuming that NOM, Fe(II), and nitrate (NO₃⁻) are the only species present in the raw water that absorb UV light in significant quantities and that all the iron present is Fe(II). The extinction coefficients for NOM in the Charnock wellfield as a function of wavelength was determined by subtracting the absorbance of water, Fe(II) and NO₃⁻ from the total background UV absorbance (Crittenden *et al.*, 2005).

When the MPUV system is used as a light source of H₂O₂ in the Charnock water, an overall fraction of light absorbed F for H₂O₂ can be calculated in a water with a given background absorbance as follows (Bolton, 1999).

$$F = G_i \times \frac{A_{\lambda, H_2O_2}}{A_{\lambda, H_2O_2} + A_{\lambda, water}}$$

(36)

G_i (= total photon flow absorbed) = $f_{\lambda} \times$ (lamp photon flow of the MPUV)

f_{λ} (= fraction of light absorbed by H₂O₂) = $1 - 10^{-A_{\lambda, H_2O_2}}$

$A_{\lambda, water}$ = absorbance at wavelength λ of raw water (cm)

where A_{λ, H_2O_2} (= absorbance at wavelength λ of H₂O₂) = $\sum_i \varepsilon_{\lambda, i} c_i l$

$\varepsilon_{\lambda, i}$ = molar absorption coefficient at wavelength λ of H₂O₂

c_i = concentration (M) of H₂O₂ (=2.94 mM)

l = pathlength (cm) (=1 cm)

Because H₂O₂ only absorbs light in the range from 200 to 300 nm, the calculated F ($i=200-300$ nm) for 10 mg/L of H₂O₂ in the Charnock wellfield is 0.0044.

(Table 5 goes here)

The second order HO• rate constant of NOM in the Charnock wellfield was calculated from the SUVA and Equation (5). Because the SUVA for NOM analyzed in the Charnock wellfield was 1.7 L/mg carbon•s, the second order HO• rate constant was calculated as 2.9×10^8 L/mole carbon•s.

Formation of tBA as a Byproduct of MtBE Oxidation tBA is produced during the oxidation of MtBE by the UV/H₂O₂ process. Based on the literature review of the MtBE oxidation pathway (Stefan *et al.*, 2000) a conservative estimation of the molar ratio of tBA formation by MtBE oxidation is approximately 10 to 15 % and 15.0 mole% was used in model calculations to be conservative. Therefore, the influent concentration of tBA that was used in the modeling is approximately 68 µg/L to account for the tBA influent concentration of 30 µg/L and the formation of tBA as a byproduct of MtBE oxidation.

Design Considerations The process design requires careful consideration of several factors, including hydrogen peroxide dosage, configuration and mixing condition of the reactors.

Hydrogen Peroxide Dosage A dosage of 10 mg/L was used as the design basis because excess H₂O₂ has to be removed. The effect of dosages higher than 10mg/L was simulated when low H₂O₂ dosage did not show significant removal and when the removal efficiency over a wide range of dosage was of interest for dosage optimization.

Physical Properties of the UV Reactors Table 6 summarizes the detailed properties of each UV reactor.

(Table 6 goes here)

LPUV Reactor System The configuration of reactors, mixing conditions, and modeling approach applied for the LPUV system are discussed below.

Configuration of Reactors Based on practical experience, the LPUV system can be implemented with several LPUV reactors in series. It was decided that the LPUV system will consist of four parallel trains each including the required number of LPUV reactors in series. The flow rate in each parallel train is 1750 gpm, such that the system can handle the peak flow of 7,000 gpm. The number of reactors in series required per train is determined using the AOP model for the case of raw water and for each of the eight pretreatment alternatives. The mixing condition in each reactor was determined by dye study data from the manufacturer and it was determined that 8 tanks in series (TIS) described reactor mixing conditions.

Modeling Approach The AOP modeling approach involved determining the appropriate number of reactors in a single train ($Q=1,750$ gpm) to meet the treatment objectives for both MtBE and tBA. To determine the number of reactors in the train, the following strategy was followed for each of the nine cases (raw water plus eight pretreatment alternatives):

- Run the AOP model with a single reactor (8 TIS). If both MtBE and tBA meet their treatment targets, then one reactor is sufficient.
- If both MtBE and tBA do not meet their treatment targets, then the model is run for two reactors, which consists of solving the AOP model equations for 16 TIS

because the mixing condition in each reactor is described by 8 TIS, as discussed above. If both MtBE and tBA meet their treatment targets, then two reactors are sufficient.

- If the treatment goals were not met with two reactors in series, then run the model for three reactors (24 TIS).
- The number of reactors was increased up to 9 maximum reactors or until the treatment targets for MtBE and tBA are met.

If during the process, it proved impossible to meet the treatment targets for a hydrogen peroxide dosage of 10 mg/L, the dosage was increased and the strategy above was repeated.

MPUV System The configuration of reactors, mixing condition, and modeling approach applied for the MPUV system are discussed below.

Configuration of Reactors The size of the MPUV reactor is about four times larger than the LPUV reactor. There is no evidence available from the manufacturer that it would be appropriate to configure a large number of MPUV reactors in series. Therefore, the approach taken was to allow for no more than two reactors in series in the design. The number of parallel trains consisting of one or two reactors was determined, such that the treatment targets for MtBE and tBA could be achieved for the raw water and for each of the eight pretreatment alternatives.

No data were available from the manufacturer to analyze the mixing condition in the MPUV reactor. Based on a rough estimate using a correlation for a long pipeline without bends, restrictions, or disturbances to flow, four TIS was chosen to describe the mixing condition in each MPUV reactor.

Modeling Approach The AOP modeling approach involved determining the appropriate number of parallel trains consisting of one or two reactors in each train (that is, determine Q for each parallel train) to meet the treatment objective for both MtBE and tBA. To determine the number of parallel trains consisting of one or two reactors, the following strategy was followed for each of the nine cases (raw water plus eight pretreatment alternatives):

- Run the AOP model with a single reactor (4 TIS). If both MtBE and tBA meet their treatment targets, then it has been determined that one reactor is sufficient.
- If both MtBE and tBA do not meet their treatment targets, then the model is run for two reactors, which consists of solving the AOP model equations for 8 TIS because the mixing condition in each reactor is described by 4 TIS. If both MtBE and tBA meet their treatment targets, then two reactors are sufficient.
- If the treatment targets were not met, then the model would then be run with a reduced flow rate, assuming that there are two parallel trains, each of which contains two reactors in series (Q=3500 gpm in each train). Each parallel train would be treated as having 8 TIS to account for the mixing condition. If the treatment targets for MtBE and tBA are achieved, then no additional parallel reactors would be required.
- On the other hand if the treatment objectives could not be met, the number of parallel trains, each of which consists of two reactors in series, would be increased until the treatment targets for MtBE and tBA are met. The process would be continued until 9 parallel trains (18 reactors) are used. For the case of 18

reactors, the system would include 9 trains with two reactors in series per train (Q=778 gpm in each train).

If during the process, it proves impossible to meet the treatment targets for the hydrogen peroxide dosage of 10 mg/L, the dosage can be increased and the strategy above was repeated.

Results and Discussion

Table 7 summarizes the dose of H₂O₂, the EE/O of MtBE and tBA, the effluent concentration of MtBE and tBA, and the number of reactors per train for the raw water and 8 different pretreatment alternatives for both the LPUV and the MPUV system. According to the model calculations, the raw water requires 4 parallel trains of 9 LPUV reactors in series, (36 reactors in total), or 8 trains of 2 MPUV reactors in series (16 reactors in total). The H₂O₂ dosage and residual H₂O₂ concentration are reported and this can have a significant impact on the treatment plant costs because H₂O₂ residual has to be removed and high dosages of H₂O₂ increase the cost of chemical addition. From the EE/O calculation, tBA is the controlling contaminant in this case. The EE/O for treating the tBA in the raw water is as high as 4.4 and 23 kWh/kg/gal for the LPUV and the MPUV system, respectively. Considering the large flow rate of the site, it is cost prohibitive to treat the raw water, especially for the MPUV system. However, some site-specific characteristics, such as space availability, public acceptability, local regulations, etc. have to be considered.

(Table 7 goes here)

Except the Pellet reactor pretreatment option, all the pretreatment alternatives improve the efficiency of both UV systems and thus decrease the EE/O and the number of the

photo-reactors. Under the design conditions, the NaIX, the pellet reactor, and WAIX provide the same performance if followed by dealkalization. However, both the pellet reactor and the WAIX have a significantly higher capital cost than does the use of the existing NaIX. Among all pretreatment alternatives, reverse osmosis (RO) gives the best effluent water quality and achieves the least EE/O and requires the least number of reactors. For the LPUV system, 4 trains of the LPUV reactors with 1 reactor in each train (a total of 4 LPUV reactors), suffice to treat the RO pretreated water with H₂O₂ dosage lower than 7 mg/L compared to 10 mg/L for the each of the other pretreatment alternatives with dealkalization. In the case of the LPUV system, water prepared by the RO pretreatment requires only 15% of the power for treatment as does the water from each of the other pretreatment alternatives with dealkalization. For the MPUV system, only 2 MPUV reactors will be required for RO pretreated water and 1 reactor is enough when dealkalization is used.

However, RO is an energy intensive process and it is not practical to apply it for AOP pretreatment if other pretreatment methods produce EE/O values that are reasonable. The lime softening pretreatment considered to ensure adequate performance of the RO is also cost prohibitive. In addition, the brine from the RO process must be treated to remove MtBE and tBA and the concentration of the MtBE and tBA in the brine could be much higher than the concentration in the raw water. For these reasons, the RO was ruled out as an appropriate pretreatment strategy.

Dealkalization significantly improves the AOP efficiency for all pretreatment technologies. Without the dealkalization, the number of reactors required for the four pretreatment alternatives is in the order of RO < WAIX < NaIX < Pellet for both the

MPUV and the LPUV system. With dealkalization, the number of reactors required for WAIX, NaIX and Pellet is almost the same.

Because the pellet reactor pretreatment alternative without dealkalization has a high pH of 9.1, there is a significant amount of carbonate ion in the system, which makes it very difficult for the AOP to meet the treatment targets, as compared to the other pretreatment alternatives and the raw water.

Impact of NOM, Carbonate species, pH and Fe²⁺

At the Charnock wellfield, NOM and bicarbonate species have the most impact on the efficiency of the AOP process. The relative importance of the two species for scavenging hydroxyl radicals can be estimated according to Equations (4) and (6). NOM is more detrimental to AOP performance because it also interferes the UV absorbance by H₂O₂. However, without reduction of NOM, the removal of all carbonate species only reduces the total number of required reactors from 36 in the raw water to 24 for the LPUV system or from 16 for the raw water to 10 for the MPUV system. Further reduction of NOM, as measured by TOC, to 0.07 mg/L can reduce the required number of reactors down to 4 for the LPUV system or 1 for the MPUV system.

When the concentration of carbonate species is as high as 200 mg/L, i.e., the case for pellet softening, high pH is detrimental to the UV/H₂O₂ process. High pH also favors the dissociation of H₂O₂ into HO₂⁻ ion and the later has an extinction coefficient 10 times larger than H₂O₂ but this does not offset the quenching of HO• by the high concentration of carbonate species. For example, increasing the pH from 7.6 to 9.1 requires 8 more LPUV reactors or 2 more MPUV reactors, in spite of the fact that the total alkalinity decreased from 318 to 203 mg/L as CaCO₃ using Pellet softening. On the other hand, for

the acidic pH range from 4.4 to 4.75, the performance of the UV/H₂O₂ process for the NaIX, WAIX, and Pellet Softening pretreatment processes were nearly identical. The reasons are: 1) there is no more carbonate and bicarbonate present; 2) it is far below the pK_a of H₂O₂ and thus has negligible impacts on the dissociation of H₂O₂; 3) MtBE and tBA do not dissociate. Therefore, it is important to consider the actual water quality and the contaminants of interest when estimating the impact of pH for the UV/H₂O₂ process.

Fe(II) as a reductive species has little influence in this case. However, for the LPUV system, 0.44 mg/L of Fe(II) in the raw water requires 1 more reactor for each of the 4 trains to achieve treatment objectives. Another reason for removal of Fe(II) prior to UV system is to prevent scaling on the sleeves of UV lamps.

Impact of H₂O₂ dosage

Based on lowest cost, less residuals handling and less complexity, the NaIX+Dealkalization pretreatment process was chosen as the preferred process. Consequently, the number of reactors per train required to achieve the treatment objectives using this process were evaluated for various H₂O₂ dosages. The results are shown in Table 8. At a 10 mg/L dosage of H₂O₂, at least 6 reactors are required for each of the 4 trains, that is, 24 reactors in all are required. If the dosage is increased to 20 mg/L, 4 reactors in each train, or 16 reactors in all are able to treat the water to meet the treatment objectives.

According to the chain reaction mechanism of the hydroxyl radical (HO•) system, H₂O₂ can be a HO• scavenger if too high of a dosage is used. Dosages between 10 and 20 mg/L are below the optimal dosage, and the deleterious effect of the scavenging of

hydroxyl radicals by H_2O_2 is not observed. As a result, the EE/O increases as H_2O_2 dosage increases.

If the number of the tanks is fixed, increasing H_2O_2 dosage might achieve higher reductions of MtBE and tBA up to a point. However, higher dosages of H_2O_2 lead to higher chemical costs and higher H_2O_2 residual concentrations. This will increase the demand of hypochlorite necessary which was chosen to reduce the H_2O_2 residual. In addition, high hypochlorite dosages will result in higher chlorate concentrations in the effluent because this is a common contaminant in the hypochlorite solution.

(Table 8 goes here)

The H_2O_2 dosage optimization results for the LPUV system are shown in Figure 1. With 6 reactors per each train, both EE/O of MtBE and tBA readily decrease as the H_2O_2 dose increases. Based on the fact of the EE/O, it is likely that the optimum dosage of H_2O_2 is over 20 mg/L of the H_2O_2 dose. However, the cost required for 20mg/L of H_2O_2 dosage overweigh the energy cost in this case. Thus, 10 mg/L of H_2O_2 dose is for a good choice for the LPUV system.

(Figure 1 goes here)

The impact of H_2O_2 dosage on the MPUV system has also been conducted and was very similar to the discussion above.

Evaluation on Pretreatment Alternatives

As shown above, NaIX+Dealkalization, Pellet+Dealkalization, and WAIX+Dealkalization pretreatment alternatives do not make any difference in terms of the influent water qualities for the UV/ H_2O_2 process. When it comes to the overall treatment process including the UV/ H_2O_2 process, NaIX+Dealkalization pretreatment is

the preferred alternative because of the following reasons: i) the elimination of competitive reactants such as alkalinity, iron and manganese, ii) the elimination or reduction of the scale forming components such as iron, manganese and calcium, iii) it is the existing process so more cost effective than installing a new process. Pellet pretreatment can remove Calcium hardness by adding NaOH prior to an upflow fluidized bed of CaCO_3 crystals. However, it produces a turbid product water that requires further filtration due to spontaneous crystallization of CaCO_3 that occurs when the treatment chemicals are first introduced into the water. Moreover, the magnesium hardness and unusually high silica in the Charnock wells are not removed by the pellet pretreatment and this leaves significant amounts of hardness in the effluent. Although the WAIX pretreatment process removes more alkalinity than the NaIX pretreatment process and can reduce magnesium, calcium and TDS, the capital cost of the WAIX pretreatment process is higher than other pretreatment alternatives and an acid regeneration is required. Consequently, the NaIX pretreatment alternative is likely to be the most appropriate pretreatment alternative followed by the UV/ H_2O_2 process at this site.

Comparison of the LPUV and the MPUV system

The EE/O of the MPUV system is generally several times higher than that of the LPUV system for all the pretreatment alternatives, which represents a higher energy requirement. The model calculation indicates 4 trains of the LPUV reactors with 6 reactors in series per train (24 reactors in total), while 5 trains of the MPUV reactors with 2 reactors in series per train (10 reactors in total) are required to treat the water after NaIX with Dealkalization. The energy requirement for the MPUV system is about five times more than that of the LPUV system. The major reason is that not all irradiation

from MPUV can be effectively absorbed by H_2O_2 . In addition, the extinction coefficient of NOM in this site is high for the wavelengths less than 240 nm and therefore, most irradiation below 240 nm would be absorbed by NOM. Because the concentration and characteristic of NOM differs from site to site, the impact on performance would vary accordingly. One advantage of the MPUV system is that less lamps are needed to achieve the same amount of energy input, which may be easier to operate and maintain. Therefore, the final selection of the processes needs carefully consider all the factors that were discussed here.

Cost Comparison

A rough cost comparison of the energy and H_2O_2 is presented in Table 9 for the NaIX pretreatment with Dealkalization. The unit prices for H_2O_2 and electrical energy used in the calculation are \$1.5/lb and \$0.10/kWh, respectively. The cost of energy for the MPUV reactor system is 5 times higher than for LPUV reactor system.

(Table 9 goes here)

If the number of the LPUV reactors is less than 12, the energy cost will be less than the chemical cost. In this case, the EE/O alone is not appropriate to evaluate the feasibility of using the UV/ H_2O_2 process for removal of MtBE and tBA and therefore, both the EE/O and the dosage of H_2O_2 have to be considered. In the design process, a comparison of the EE/O versus the H_2O_2 dosage provides valuable insight into the tradeoffs and support determination an appropriate H_2O_2 dosage.

Conclusion

Although a UV/ H_2O_2 system has been shown to remove many organic contaminants, raw waters with high TOC and carbonate species may not be easily treated. In such

cases, it is beneficial to pretreat the water to remove TOC, carbonate species and iron and manganese in the raw water. Kinetic models can be used to simulate the complex interaction of those factors and removal efficiency and this provides useful information on the benefits of different pretreatment options. In the Charnock wellfield, removal of carbonate species using pretreatment processes can reduce the energy cost by much as 1/3 and reduce the number of reactors from 36 to 24 which would translate into a capital cost savings by 1/3. For the LPUV system, the cost of chemicals can be as high as the energy cost.

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Table 1. Raw water quality in the Charnock wellfield

Parameter	units	value	Parameter	units	value
Conductivity	mmho/cm	1435	Aluminum	mg/L	0.005
TDS	mg/L	940	Potassium	mg/L	11.4
Alkalinity	mg/L CaCO ₃	313	Iron	mg/L	0.44
Calcium	mg/L	138	Manganese	mg/L	0.089
Hardness	mg/L	533	Fluoride	mg/L	0.29
Chloride	mg/L	138	Bromide	mg/L	0.9
Nitrate	mg/L NO ₃ ⁻	0.9	pH	unitless	7.56
Sulfate	mg/L	272	MtBE	µg/L	300
Sodium	mg/L	107	TOC	mg/L	1.35
Magnesium	mg/L	54	tBA	µg/L	30

Table 2. Important elementary reactions that are involved in the H₂O₂/UV process at near neutral pH

No	Reactions	Rate constants, M ⁻¹ s ⁻¹	Reference
8	H ₂ O ₂ + hv → 2HO•	$r_{UV/H_2O_2} = -r_{HO\bullet} / 2 = -\phi_{H_2O_2} I_0 f_{H_2O_2} (1 - e^{-A})$ $A = 2.303b(\epsilon_{H_2O_2} C_{H_2O_2} + \epsilon_{R1} C_{R1} + \epsilon_{NOM} C_{NOM})$ $f_{H_2O_2} = 2.303b(\epsilon_{H_2O_2} C_{H_2O_2} + \epsilon_{HO_2^-} C_{HO_2^-}) / A$ $\epsilon_{H_2O_2, 254nm} = 17.9 \sim 19.6 \text{ M}^{-1} \text{ cm}^{-1}$ $\phi_{H_2O_2} = \phi_{HO_2^-} = 0.5$	Hunt <i>et al.</i> , 1952
9	R + hv → Products	$r_{UV,R} = -\phi_R I_0 f_R (1 - e^{-A})$ $f_R = 2.303b \epsilon_R C_R / A$	photolysis rate
10	HO• + HO ₂ ⁻ $\xrightarrow{k_9}$ OH ⁻ + HO ₂ •	K ₁₀ = 7.5 × 10 ⁹ 1982	Christensen <i>et al.</i> ,
11	HO• + H ₂ O ₂ $\xrightarrow{k_{10}}$ H ₂ O + HO ₂ •	k ₁₁ = 2.7 × 10 ⁷	Buxton <i>et al.</i> , 1988
12	HO• + HCO ₃ ⁻ $\xrightarrow{k_{11}}$ CO ₃ ⁻ • + H ₂ O	k ₁₂ = 8.5 × 10 ⁶	Buxton <i>et al.</i> , 1988
13	HO• + R $\xrightarrow{k_{12}}$ Products	k ₁₃ ,	
14	HO• + NOM $\xrightarrow{k_{13}}$ Products	k ₁₄ = 3 × 10 ⁸ to 4.5 × 10 ⁸ (average = 3.8 × 10 ⁸) L/mole NOM carbon•s 1999	Westerhoff <i>et al.</i> ,
15	HO• + CO ₃ ²⁻ $\xrightarrow{k_{14}}$ CO ₃ ⁻ • + OH ⁻	k ₁₅ = 3.9 × 10 ⁸ 1988	Buxton <i>et al.</i> ,
Acid dissociation constants			
16	H ₂ CO ₃ * ↔ H ⁺ + HCO ₃ ⁻	pK _{a1} = 6.3	Stumm <i>et al.</i> , 1996
17	HCO ₃ ⁻ ↔ H ⁺ + CO ₃ ²⁻	pK _{a2} = 10.3	Stumm <i>et al.</i> , 1996
18	H ₂ O ↔ H ⁺ + OH ⁻	pK _{a3} = 14	Stumm <i>et al.</i> , 1996
19	H ₂ O ₂ ↔ H ⁺ + HO ₂ ⁻	pK _{a5} = 11.75	Perry <i>et al.</i> , 1981
20	HO ₂ • ↔ H ⁺ + O ₂ ⁻ •	pK _{a6} = 4.8	Perry <i>et al.</i> , 1981

Table 3. Rate equations that are involved in the H₂O₂/UV process.

Rate equations	No.
$r_{HO\bullet} = 2\phi_{H_2O_2} I_o f_{H_2O_2} (1 - e^{-A}) - k_{10} [HO\bullet][HO_2^-] - k_{11} [HO\bullet][H_2O_2]$ $- k_{12} [HO\bullet][HCO_3^-] - k_{13(MTBE)} [HO\bullet][MTBE] - k_{13(TBA)} [HO\bullet][TBA]$ $- k_{14} [HO\bullet][NOM] - k_{15} [HO\bullet][CO_3^{2-}]$	(21)
$r_{H_2O_2} = r_{UV, H_2O_2} - k_{11} [HO\bullet][H_2O_2] - k_{10} [HO\bullet][HO_2^-]$	(22)
$r_{HO_2\bullet} = k_{11} [HO\bullet][H_2O_2] + k_{10} [HO\bullet][HO_2^-]$	(23)
$r_{CO_3\bullet} = k_{12} [HO\bullet][HCO_3^-] + k_{13} [HO\bullet][CO_3^{2-}]$	(24)
$r_{MTBE} = -k_{13(MTBE)} [HO\bullet][MTBE]$	(25)
$r_{TBA} = -k_{13(TBA)} [HO\bullet][TBA]$	(26)
$r_{NOM} = -k_{14} [HO\bullet][NOM]$	(27)
$[HCO_3^-] = \frac{K_{a1} [H_2CO_3^*]}{[H^+]}$	(28)
$[CO_3^{2-}] = \frac{K_{a2} [HCO_3^-]}{[H^+]}$	(29)
$[OH^-] = \frac{K_{a3}}{[H^+]}$	(30)
$[HO_2^-] = \frac{K_{a5} [H_2O_2]}{[H^+]}$	(31)
$[O_2\bullet] = \frac{K_{a6} [HO_2\bullet]}{[H^+]}$	(32)

|

Table 4. Influent Water Quality After Pretreatment

Alternative	TOC (mg/L)	Alkalinity (mg/L as CaCO ₃)	pH	Ferrous Iron (mg/L)
Raw water	1.4	318	7.6	0.44
NaIX	1.4	318	7.6	0
NaIX + Dealkalization	1.4	0	4.65	0
Pellet Softening	1.4	203	9.1	0
Pellet Softening + Dealkalization	1.4	0	4.75	0
WAIX	1.4	118	6	0
WAIX + Dealkalization	1.4	0	4.4	0
RO	0.07	54.1	7	0
RO + Dealkalization	0.07	0	4.5	0

Table 5. Absorbance of raw water of the Charnock wellfield, iron(II), nitrate, calculated NOM, and fraction of light absorbed by H₂O₂ in the range from 200 to 300 nm of wavelength for a MPUV reactor.

Wavelength (nm)	Absorbance (1/cm)				Lamp photon flow (rel)	Total photon flow absorbed	Photon flow absorbed by H ₂ O ₂
	Raw water	Fe(II)	Nitrate	NOM			
200	0.909	0.0052	0.1346	0.769	26.67	3.043	0.1666
210	0.546	0.0054	0.1097	0.430	35.59	3.306	0.2381
220	0.239	0.0052	0.0531	0.181	39.45	2.582	0.2828
230	0.067	0.0041	0.0125	0.050	28.39	1.204	0.2649
240	0.027	0.0047	0.0015	0.021	29.26	0.751	0.2219
250	0.022	0.0042	0.0001	0.017	46.54	0.694	0.1617
260	0.019	0.0030	0.0000	0.016	47.60	0.395	0.0631
270	0.017	0.0025	0.0000	0.015	19.18	0.086	0.0086
280	0.017	0.0023	0.0000	0.014	12.76	0.029	0.0017
290	0.016	0.0021	0.0001	0.013	15.55	0.017	0.0005
300	0.015	0.0020	0.0001	0.013	21.40	0.012	0.0002
Totals					322	12.1	1.41

Table 6. Comparison of the LPUV reactor and the MPUV reactor associated with the physical properties and lamp efficiency.

	LPUV	MPUV
Diameter, D (inches)	30	48
Length, L (inches)	148	180
Number of lamps	144	18
Nominal power per lamps (kW)	0.25	25
UV efficeincy of lamps (%)	35-40	10-15
Wavelength of emit (nm)	254	200-300*

* wavelength for hydrogen peroxide to absorb photons

Table 7. Summary of results for all the pretreatment alternatives

Pretreatment Process	H ₂ O ₂ (mg/L)		EE/O (kWh-kgal/order)		Effluent Concentration (µg/L)		No. of reactors per train	No. of trains
	In	out	MtBE	tBA	MtBE	tBA		
LPUV System								
None (raw)	25	13	1.1	4.4	0.5	5.7	9	4
NaIX	25	13	1.0	4.0	0.6	6.0	8	4
NaIX + Dealkalization	10	6.9	0.77	3.0	0.6	5.8	6	4
Pellet	70	35	1.4	5.3	0.4	5.4	11	4
Pellet + Dealkalization	10	6.9	0.77	3.0	0.6	5.8	6	4
WAIX	10	6.3	0.83	3.1	0.3	4.7	7	4
WAIX + Dealkalization	10	6.9	0.77	3.0	0.6	5.8	6	4
RO	7.0	4.9	0.15	0.49	1.3	5.7	1	4
RO + Dealkalization	4.0	2.9	0.11	0.29	0.2	1.8	1	4
MPUV System								
None (Raw)	30	15	7.3	23	1.3	5.2	2	8
NaIX	30	12	6.2	18	0.5	3.4	2	8
NaIX + Dealkalization	10	6.6	4.6	15	1.4	5.8	2	5
Pellet	50	19	8.3	27	1.4	5.9	2	9
Pellet + Dealkalization	10	6.6	4.6	15	1.4	5.8	2	5
WAIX	10	5.9	5.2	16	1.0	4.8	2	6
WAIX + Dealkalization	10	6.6	4.6	15	1.4	5.9	2	5
RO	4	1.9	0.99	2.8	2.1	5.0	1	2
RO + Dealkalization	3	2.2	0.48	1.3	1.8	4.5	1	1

Table 8. Modeling results for using 4 trains of LPUV reactors to treat water with NaIX+
Dealkalization pretreatment

number of reactors per train	H ₂ O ₂ (mg/L)		Effluent concentration (µg/L)		EE/O (kWh/kgal-order)	
	dosage	residual	MtBE	tBA	EE/O (MtBE)	EE/O (tBA)
4	20	16	0.65	5.9	0.53	2.0
5	14	11	0.46	5.2	0.63	2.3
6	8	5.5	1.36	8.3	0.90	3.8
6	10	6.9	0.55	5.8	0.77	3.0
6	12	8.4	0.26	4.3	0.69	2.5
6	14	9.9	0.14	3.3	0.63	2.2
7	10	6.5	0.22	4.0	0.79	2.8
7	12	7.9	0.09	2.8	0.70	2.4
7	14	9.3	0.04	2.1	0.64	2.1

Table 9. Cost comparison for the design comparing of the LPUV reactor and the MPUV reactor

	Number of reactors	Total power per day (kWh)	Cost of energy (\$/day)	H ₂ O ₂ dose (mg/L)	Total amount per day (lb)	Cost of chemical (\$ per day)
LPUV system	24	21,300	\$2,130	10	600	\$899
MPUV system	10	108,000	\$10,800	10	600	\$899

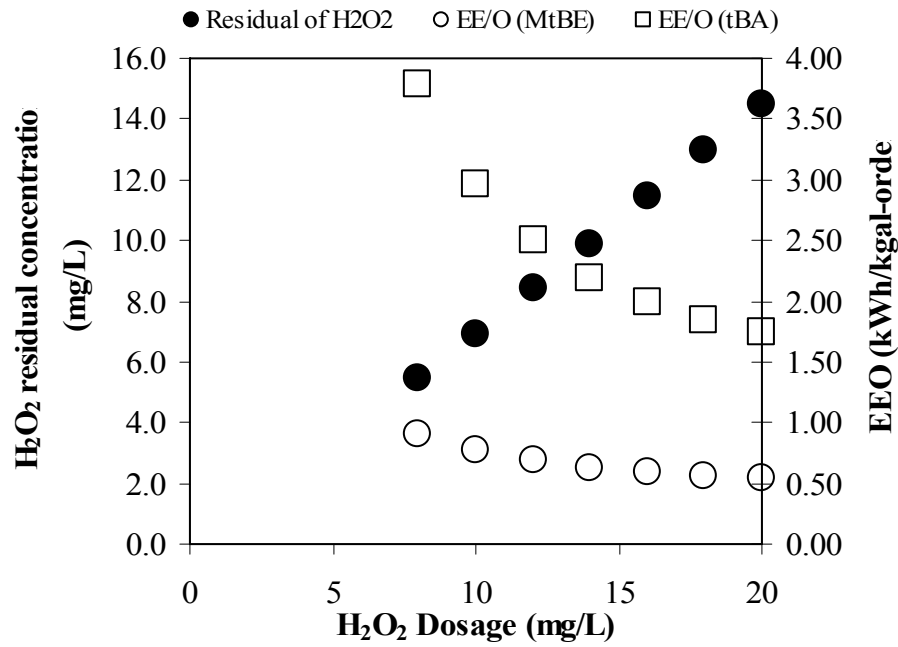


Figure 1. Impact of Varying Hydrogen Peroxide Dosage Using 24 LPUV Reactors, Corresponding to the NaIX+Dealkalization Pretreatment Alternative