Water Treatment – Advanced Oxidation Processes

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Module 1: Introduction

Learning Objectives

By the end of this section, you will be able to:

- **Evaluate** the comparative effectiveness of ultraviolet (UV) irradiation and ozonation for the removal of organic micropollutants in drinking water.
- **Identify** the fundamental features and mechanisms, such as DNA reaction and dose-response relationships, that allow UV light to effectively disinfect protozoa.
- **Analyze** the specific technical and regulatory challenges associated with treating contaminants like Bromate, MTBE, NDMA, and Perchlorate using advanced oxidation processes (AOPs).

Executive Summary: This chapter evaluates and compares ultraviolet (UV) irradiation and ozone, both independently and with the addition of hydrogen peroxide (H_2O_2), for the removal of micropollutants. While traditional disinfectants like chlorine and ozone provide multiple benefits—including disinfection and oxidation—within a narrow dosage range, this research examines if UV can provide similar multi-benefit performance at low doses to reduce utility electrical usage and minimize the formation of regulated disinfection by-products (DBPs) like bromate.

Background and Overview

Traditional disinfectants often provide multiple benefits in a single application. For instance, **chlorine** is used for pathogen disinfection, iron/manganese oxidation, and algae control. **Ozone** offers these same advantages while also inactivating **Cryptosporidium** oocysts and reducing taste-and-odor (T&O) compounds. Typically, the doses required for these objectives do not differ by more than a factor of two or three.

UV disinfection is receiving increased attention in the drinking water industry because of its newfound ability to disinfect protozoa. This ability has been unveiled by three fundamental features:

1. The mechanism through which UV photons react with **intracellular DNA**.
2. The significant reduction of **Cryptosporidium** when compared to experiment controls.
3. A defined **UV dose-response relationship**.

Potential benefits of UV technologies include high levels of microbial disinfection, low operating costs, and minimal DBP formation. This study investigates if UV can control emerging contaminants like **NDMA** and **MTBE**, manage T&O oxidation, and remain complimentary with other treatment goals (reducing **bromate** and **perchlorate**) at low UV doses (less than 100 mJ/cm2).

Bromate

Many U.S. drinking water plants have switched from chlorine to ozonation to comply with lower DBP regulations. A significant concern with ozonating natural waters is the formation of the ozonation by-product **bromate**.

- **Formation**: Bromate forms through complex reactions between ozone, bromide, TOC, and hydroxyl radicals.
- **Regulatory Limit**: Bromate is a suspected human carcinogen regulated by the USEPA at a Maximum Contaminant Level (MCL) of **0.010 mg/L**.
- **Control Issues**: Reducing the pH of ozonation can combat bromate formation, but pH adjustment typically increases **Total Dissolved Solids (TDS)**, decreasing aesthetic water quality.

MTBE

Methyl tert-butyl ether (MTBE) is a common oxygenated fuel additive, typically added to gasoline at 11 percent by volume. Its high solubility makes effective removal from water challenging.

- **Occurrence**: In southern California, MTBE has been detected in groundwater wells and surface water supplies.
- **Standards**: The State of California Department of Health Services (CDHS) has established a primary standard of **13 microgram/L** and a secondary standard of **5 microgram/L**.
- **Treatment Options**: Air stripping and Granular Activated Carbon (GAC) are feasible, but high concentrations require tall towers or frequent carbon regeneration, leading to high operational costs.
- **Oxidation Pathways**: MTBE oxidation is primarily accomplished by the **hydroxyl radical**. Direct oxidation by molecular ozone is very slow, while oxidation by hydroxyl radicals is extremely rapid.

NDMA

N-nitrosodimethylamine (NDMA) is a by-product of rocket fuel and various manufacturing processes.

- **Health Risk**: The USEPA identifies NDMA as a probable human carcinogen.
- **Action Level**: In 1998, the CDHS announced an action level of **0.002 microgram/L** for NDMA.
- **Treatment Limitations**: NDMA is **not** removed by air-stripping, reverse-osmosis membranes, or GAC due to its high water-solubility and polar nature.
- **UV Performance**: NDMA can be reduced by UV technologies because it strongly absorbs UV light. Low-pressure mercury UV lamps have shown reduction of NDMA from 0.089 to 0.005 microgram/L at a dosage of approximately **2.6 kWh/m3**.

Perchlorate

Ammonium perchlorate is used in the manufacturing of solid rocket fuels and explosives. The compound is stable in water and does not readily decompose.

- **Health Concerns**: At high concentrations, it can interfere with the thyroid gland's ability to utilize iodine to produce metabolic hormones.
- **Action Level**: CDHS has established a provisional action level of **18 microgram/L**.
- **Current Technologies**: Physicochemical processes like ion-exchange and membrane processes merely remove the chemical and create a waste concentrate. Biological reduction can break it down to harmless chloride and oxygen but is not a widely adopted method for drinking water.

T&O Compounds

Taste-and-odor (T&O) problems often result from algal blooms in raw water reservoirs.

- **Common Compounds**: These include **2-methylisoborneol (MIB)** and **geosmin**.
- **Advanced Oxidation**: UV radiation of **H_2O_2** produces the hydroxyl radicals required for treatment.
- **Efficiency**: Research indicates that a UV energy of 3.5 kWh/1,000 gal combined with **20 mg/L H_2O_2** can remove up to **95 percent** of geosmin.

Checkpoint Quiz

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1. **Which factor is a primary reason for the drinking water industry's increased focus on UV disinfection?**
   a) Its ability to provide a durable chemical residual for distribution.
   b) Its proven effectiveness in inactivating protozoa such as Cryptosporidium.
   c) Its capacity to lower Total Dissolved Solids (TDS) during treatment.
   d) Its use as the leading method for removing perchlorate via air-stripping.

Answer: (b). Research has established a clear dose-response relationship and identified the mechanism of DNA reaction.

2. **Why is Granular Activated Carbon (GAC) considered an ineffective alternative for treating high concentrations of MTBE?**
   a) It creates hazardous bromated by-products.
   b) It requires frequent carbon regeneration, resulting in high operational costs.
   c) It cannot be used in waters with a pH higher than 8.0.
   d) MTBE's high solubility prevents any adsorption to the carbon surface.

Answer: (b). While feasible for low concentrations, high levels of MTBE saturate the GAC quickly.

3. **True or False: NDMA is effectively removed from water using standard reverse-osmosis membranes and air-stripping technologies.**
   a) True
   b) False

Answer: (b). NDMA is not removed by these methods because of its high water-solubility and polar nature.

Module 2: Project Objectives

Learning Objectives

By the end of this section, you will be able to:

- **Identify** the specific water quality and operational parameters evaluated for bromate, MTBE, and NDMA reduction.
- **Evaluate** the impact of auxiliary compounds, such as t-butyl alcohol (TBA) and nitrate, on the efficiency of advanced oxidation processes (AOPs).
- **Analyze** the feasibility of using catalysts and pH adjustment to enhance perchlorate reduction via pulsed-UV technology.

Executive Summary: The project objectives establish a comprehensive framework for evaluating pulsed-UV and ozone/PEROXONE technologies across four contaminant classes. By isolating variables such as water matrix, chemical dosage, and influent concentration, the study aims to identify optimal treatment conditions while monitoring for the formation of regulated oxidation by-products.

Bromate Reduction by Pulsed UV

Bromate tests were conducted to study the effect of several parameters:

- **Water Matrix**: Two different matrices were studied.
- **UV Dose Measurement**: Two distinct techniques were used to measure the UV dose.
- **Bromate Concentration**: Testing was performed using three different concentrations.
- **Application of H_2O_2**: The research evaluated the impact of adding hydrogen peroxide to the process.

MTBE Reduction by Pulsed UV and Ozone/PEROXONE

The objectives for treating Methyl tert-butyl ether (MTBE) focused on dose optimization and the identification of secondary by-products.

Pulsed UV with H2O2 Objectives

- Determine the **optimum UV and H_2O_2 dose** for MTBE reduction.
- Evaluate the impacts of **t-butyl alcohol (TBA)** on MTBE destruction efficiency.
- Identify secondary **by-products**, including bromate, aldehydes, t-butyl formate (TBF), isopropyl alcohol, and acetone.