Energy Efficient Industrial Waste Treatment Technologies

Scoping Report

1016110

Energy Efficient Industrial Waste Treatment Technologies

Scoping Report

1016110

Technical Update, October, 2007

EPRI Project Manager

K. R. Amarnath

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Energy and Environmental Analysis, Inc., an ICF International Company

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

CITATIONS

This document was prepared by

Energy and Environmental Analysis, Inc.
An ICF International Company
12011 NE First Street, Suite 210
Bellevue, WA 98005

Principal Investigators
S. Knoke, R. Tidball

This document describes research sponsored by the Electric Power Research Institute (EPRI).

This publication is a corporate document that should be cited in the literature in the following manner:

Energy Efficient Industrial Waste Treatment Technologies: Scoping Report. EPRI, Palo Alto, CA: 2007 Product ID # 1016110.

PRODUCT DESCRIPTION

Rising energy costs coupled with the continuing need for effective environmental treatment methods have stimulated interest in advanced energy-efficient technologies. EPRI has reviewed a wide variety of electricity-based processes for industrial air pollution control, wastewater treatment, and solid waste treatment along with some closely related competing technologies. These technologies ranged from untested concepts to well-established ones. While most offer process cost savings and improvements over existing technologies, these advanced technologies have not generally been widely adopted by the industry for various reasons.

Results & Findings

This report examines a total of 53 advanced technologies applicable to industrial waste treatment. The results of this screening yielded six promising advanced industrial waste treatment technologies, as follows:

- Advanced oxidation process—photooxidation (ultraviolet/O_3/H_2O_2)
- Electrodewatering in belt filter presses
- Electrohydraulic cavitation induced by ultrasonic irradiation (sonolysis)
- Electrolysis—electrokinetic in situ remediation of groundwater and soil at hazardous waste sites
- Supercritical water oxidation
- Ultraviolet disinfection using monochromatic lamps

Of these, ultraviolet disinfection using monochromatic lamps was selected for a more thorough investigation to be reported in an EPRI TechApplication.

Challenges & Objective(s)

The challenge is to find ways for industrial account executives at electric utilities to help customers improve the energy efficiency of waste treatment processes or to build electric market share in the industrial sector. The objective of this scoping report was to examine energy-efficient industrial waste treatment technologies that could help meet this challenge.

Applications, Values & Use

In the next few years, industrial customers will most likely feel pressure to increase energy efficiency, decrease environmental impact, and reduce greenhouse gas emissions. Advanced technologies for industrial waste treatment offer an avenue to address such issues. Large numbers of advanced technologies are under development; the challenge is to match the technologies with the optimal waste treatment application. EPRI will help electric utilities stay informed about future developments in this area.

EPRI Perspective

EPRI is dedicated to improving the environment in a sustainable manner. Environmental treatment processes must continue to evolve to meet future needs. The technologies evaluated in this study show tremendous potential, but all require additional research and development to reach commercial status. Electric utilities can play a key role in this development by working with their industrial customers to identify and demonstrate promising technologies.

Approach

The goal of this project was to evaluate promising advanced environmental technologies for industrial waste treatment. A wide variety of industrial and waste treatment technologies were reviewed, along with some closely related competing technologies. Advanced technologies for industrial waste treatment work in a variety of ways, for example, they

- Oxidize pathogens, volatile organic compounds, and other contaminants
- Alter the DNA of pathogens to neutralize them, destroy them, or prevent reproduction
- Crush the pathogens in a physical sense
- Cause pathogen agglomeration into large particles and then filter them or allow them to settle
- Cause chemical reactions that result in phase change, allowing easy separation

From a total of 53 advanced technologies found applicable to industrial waste treatment, the principal investigators prepared a list of six promising industrial waste treatment technologies for further evaluation, using the following screening criteria. All technologies evaluated had to be promising but not yet established. They also had to be applicable to industrial waste treatment, though technologies having other applications were not excluded. Finally, each one had to be ready for industrial waste treatment demonstration and had to be well beyond the emerging electrotechnology state. The selected technologies could be commercially available for other applications, commercially available for waste treatment in other countries, or previously demonstrated for waste treatment in United States.

Keywords

Industrial Waste Treatment
Advanced Waste Treatment Technologies
Efficient Waste Treatment Technologies
Electric Technologies

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1

INTRODUCTION

The goal of this project was to evaluate promising environmental technologies for industrial waste treatment. A wide variety of industrial and waste treatment technologies were reviewed, along with closely related competing technologies.

A total of 53 advanced technologies were examined as indicated in Table 1–1. These technologies represent potential and existing industrial technologies applicable to industrial waste treatment, including advanced oxidation processes (ozone and others), low temperature plasma processes, corona discharge processes, induction heating, and others. Electrodialysis or electrophoresis may have application in waste treatment, but are not included in this table because they are general methods of separating materials. Appendix A contains brief descriptions of each electrotechnology.

Table 1–1
Advanced Technologies for Industrial Waste Treatment

Description	Comment
Activated carbon adsorption – Vapor phase	Potential for wide-spread use
Activated carbon adsorption with electrical regeneration (Electrosolv®)	Demonstrated
Advanced oxidation processes – Catalytic oxidation	Potential for wide-spread use
Advanced oxidation processes – $O_3 + H_2O_2$	Well-established
Advanced oxidation processes – O_3 at elevated pH	Well-established
Advanced oxidation processes – Photo-oxidation (UV/O_3/H_2O_2)	Well-established in other applications
Advanced oxidation processes using catalyst and electrodes doped with elemental Nb or Ta	Bench tested
Air flotation – Bubble assisted flotation	Commercially available
Air flotation -- Conventional	Well-established
Air flotation -- Ozonated	Untested concept
Biological treatment (anaerobic digestion with ozone treatment)	Bench tested
Dielectric heating system using microwaves	Bench tested
Dielectric heating system using radio waves	Field tested but commercially available for other applications
Electro-acoustic dewatering in belt filter press	Bench tested
Electro-dewatering in belt filter press	Bench tested
Electrohydraulic cavitation induced by spark-gap discharge (lithotripsy)	Well-established in medical applications

Description	**Comment**
Electrohydraulic cavitation induced by ultrasonic irradiation (sonolysis)	Preliminary research (including EPRI demonstration 10 years ago)
Electrolysis – Cerium-catalyzed electrochemical oxidation process (CerOx®)	Was under development
Electrolysis – Electro-coagulation (conventional)	Well-established
Electrolysis – Electro-coagulation using stainless steel cathodes and iron anodes	Bench tested
Electrolysis – Electrokinetic in-situ remediation of groundwater and soil at hazardous waste sites	Small-scale demonstrations in the field
Electron beam irradiation to accelerate oxidation	Under development
Electro-osmotic dewatering	Bench-scale tested for environmental applications but commercially available for other applications
Electrostatic precipitation	Well-established
Freeze concentration / crystallization	Pilot-scale tested (including numerous EPRI demonstrations)
Heat pump evaporation	Well-established
Incineration – Electrically heated flameless VOC oxidizer	Commercially available
Incineration -- High-temperature fluid wall reactor (resistance heating)	Preliminary research
Incineration – Induction heating	Preliminary research
Incineration – IR furnace	Well-established
Incineration – Molten-glass furnace (resistance heating)	Well-established
Incineration – Plasma or electric-arc heating	Well-established
Incineration – Pyrolytic incinerator (resistance heating)	Preliminary research
Infrared drying using electric IR emitters	Under development
Ion exchange – Resin (conventional)	Well-established
Ion exchange – Resin for selective ion recovery	Bench tested
Low-temperature (non-thermal) plasmas	Under development
Membrane separation – Electrodialysis with bipolar membranes	Promising
Ozonation (conventional ozone oxidation)	Well-established
Ozonation for control of NOx in stack gases	Preliminary research
Ozonation for processing rubber from scrap tires	Under development
Photocatalysis with UV + TiO2	Preliminary research
Photocatalytic oxidation using specific wavelengths of light	Well-established
Plasma arc furnace for high-temperature plasma processing	Demonstrated, some types are commercially available
Plasma-assisted sludge oxidation	Bench tested

Description	Comment
Refrigerated vapor condensation	Well-established
Regenerated hydrophobic polymer sorbent for VOC control	Demonstrated in 1996
Supercritical water oxidation	Preliminary research
Thermal hydrolysis	Commercially available
UV disinfection – Monochromatic lamp	Under development
UV radiation – Broad-band lamp	Well-established
Vacuum pyrolysis (Pyrocycling™)	Under development
Wet air oxidation	Well-established

Most of the technologies in Table 1-1 offer process cost savings and process improvements over existing technologies, yet these technologies have not generally been widely adopted by industry. The adoption barriers typically include one or more of the following:

- High capital cost of advanced technologies
- Reluctance to disrupt a functioning industrial process
- Lost revenues from lower production during conversion process, which includes tuning the entire plant to optimize production with the new equipment
- High cost of certification and approvals (e.g., FDA for pharmaceutical industry and food and drink industry)

The 53 advanced technologies for industrial waste treatment were screened using the following criteria:

- Must be promising electrotechnology not yet established
- Must be applicable to industrial waste treatment (but technologies having other applications are not excluded)
- Must be ready for industrial waste treatment demonstration (beyond an emerging technology, could be a commercially available technology for other applications, could be a commercially available technology for waste treatment in other countries, could have been previously demonstrated for waste treatment in U.S.)

The results of this screening yielded six technologies, which are discussed in the next section.

2

DETAILS FOR SIX ADVANCED INDUSTRIAL WASTE TREATMENT TECHNOLOGIES

This section provides an overview of the following industrial waste treatment technologies:

- Advanced oxidation process – Photo-oxidation ($UV/O_3/H_2O_2$)
- Electrodewatering in belt filter presses
- Electrohydraulic cavitation induced by ultrasonic irradiation (sonolysis)
- Electrolysis – Electrokinetic in-situ remediation of groundwater and soil at hazardous waste sites
- Supercritical water oxidation
- UV disinfection using monochromatic lamp

Advanced Oxidation Processes – Photo-Oxidation ($UV/O_3/H_2O_2$)

Advanced oxidation processes (AOPs) are defined as near ambient temperature and pressure water treatment processes which are based on the generation of hydroxyl radicals (OH) to initiate oxidative destruction of organics. AOPs using ultraviolet (UV) light, ozone (O_3), and hydrogen peroxide (H_2O_2) individually or in pairs are well established for industrial applications and, in most cases, commercially available [1]. UV, O_3, and H_2O_2 accelerate oxidation processes alone, but are most effective when applied in triple combination. Such technologies have generally not been applied to industrial waste treatment.

Advanced oxidation processes using photo-oxidation combining UV radiation with ozone and hydrogen peroxide is a promising method for industrial wastewater treatment [2]. Many organic contaminants absorb UV energy and decompose directly. At the same time, UV energy accelerates the decomposition of O_3 and H_2O_2 molecules to form OH radicals. Since H_2O_2 is completely miscible in water, it is added ahead of the oxidation zone where the ozone is added and where the UV lamps illuminate the fluid. The more clear the liquid, the more effective UV oxidation can be. The proportions of UV, O_3, and H_2O_2 must be determined experimentally for each waste stream. Photo-oxidation processes are best suited for wastewaters with low suspended solids and organic concentrations below 1%.

An advanced oxidation process using UV and H_2O_2 is frequently used for groundwater remediation to provide drinking water in small communities [3]. Advanced oxidation processes using UV and O_3 are also used for EPA site cleanup as well as groundwater remediation to provide drinking water in small communities [3]. In particular, researchers at the University of Buffalo have demonstrated the use of ozone as effective at oxidizing metal cyanide complexes such as Fe $(CN)_6$ generated in copper and cadmium plating processes [3].

CATADOX systems are available from Spartan Environmental Technologies, LLC (Mentor, Ohio). This catalytic advanced oxidation system for industrial water treatment applications combines UV, O_3, H_2O_2, and a catalyst. The system was developed, designed, and tested by

ESCO International (Conwy, UK). The technology has been demonstrated both in the laboratory and at commercial sites. Ozono Elettronica Internazionale (OEI) S.r.l. (Milan, Italy) and ESCO have partnered to market and supply the CATADOX process. Spartan is the sole distributor of OEI products in the U.S. and Canada.

AOPs using UV light, O_3, and H_2O_2 in triple combination offer cost savings compared to competing technologies, but may or may not offer energy savings. In AOPs using O_3 and H_2O_2, they are used as oxidants instead of the more conventional chlorine. Ozone and H_2O_2 are not known to produce toxic or mutagenic substances, and less storage area is required for O_3 and H_2O_2 than chlorine. The costs involved with the $UV/O_3/H_2O_2$ process are lower than the costs for a system utilizing only ultraviolet light and O_3, because the addition of H_2O_2 allows the use of a smaller O_3 generator and less oxidants. Also, the residence times needed to decrease the concentration of a contaminant to a certain level are lower for the $UV/O_3/H_2O_2$ system than for ozone alone, UV/O_3, or UV/H_2O_2 processes.

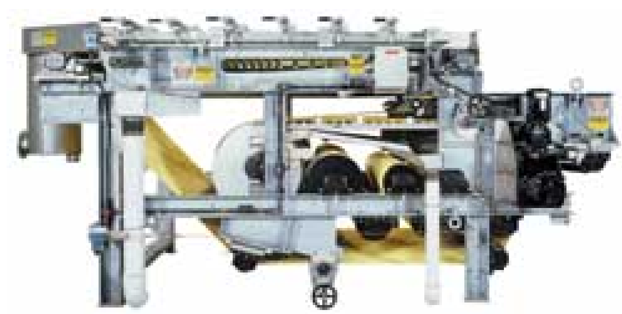
The cost of applying $UV/O_3/H_2O_2$ AOPs to industrial waste treatment is estimated to be around $2 per 1000 gallons treated. This estimate is based on an EPA analysis of using similar advanced oxidation processes to remove methyl tertiary-butyl ether (MTBE) from a contaminated well field in Southern California [4].

Table 2–1
Contact Information for Advanced Oxidation Processes Using UV, O_3, and H_2O_2

	Contact Information
For Industrial Water Treatment	
Contact Name	Anthony R. Sacco, Marketing Director
Organization	Spartan Environmental Technologies, LLC; Mentor, Ohio
Telephone	800-492-1252; 440-368-3563
E-mail Address	arsacco@SpartanWaterTreatment.com
Website	www.SpartanWaterTreatment.com
For Metal Cyanide Complexes	
Contact Name	Dr. James N. Jensen
Organization	University of Buffalo, Buffalo, NY
Telephone	716-645-2114 x2329
E-mail Address	jjensen@eng.buffalo.edu

Electrodewatering in Belt Filter Press

Electro-dewatering of sludge in a belt filter press is a patented method to increase the rate and extent of moisture reduction [5]. Figure 2–1 shows a conventional belt filter press. When a DC voltage is imposed on the sludge, the electro-osmotic driving force increases the solids content of municipal wastewater sludge from ~20% to over 40% solids [1]. The technology should be applicable to pulp and paper mills and steel mills. Electrodewatering is also an innovative method for dewatering biosolids [6]. The electric field causes electrophoresis at the initial stages, and, once a cake is formed, electro-osmosis.



Source: Komline-Sanderson

Figure 2–1
Komline-Sanderson Kompress® Belt Filter Press

Snyman et al. report on a pilot scale feasibility demonstration of this technology [7]. They report the following:

> "Sewage sludge is typically dewatered using drying beds, belt filter presses or centrifuges. Mechanical dewatering of sludge is costly in terms of capital and running costs, especially the flocculent. In an attempt to address the need for more cost-effective dewatering technologies, electro-osmotic belt filtering was developed by Smollen and Kafaar in 1995. The mechanical equipment resembles a belt filter press, but the belts are stainless steel, woven belts, which act as the electrodes. In this study, the feasibility of the technology was tested at pilot scale using waste activated-, anaerobically digested- and dissolved air flotation sludge. The parameters that were investigated include the applied voltage, polyelectrolyte usage, and sludge feed rate. Applied voltage of between 15 and 25 volts increased the dewatering significantly in the waste activated- and anaerobically digested sludge. Applying a voltage in dissolved air flotation sludge could not enhance the efficiency of dewatering, unless stored to de-air. The technology was found as sensitive to polyelectrolyte dosages as belt presses. The performance of the electro-osmotic belt filter was sensitive to feed rate, but performed well with non-thickened waste activated sludge (0.61% solids), resulting in cake solids above 20%."

Hwang and Min also report on a demonstration of this technology [8]:

> "Gravity-thickened sludge (GTS) and anaerobically-digested sludge (ADS) from a wastewater treatment plant and sludge from drying bed (DBS) from a water treatment plant were dewatered using the pilot-scale electro-osmotic belt filter press (EBFP). The results indicated that the addition of electro-osmosis greatly improved sludge dewaterability, lowering water content (WC) and heavy metal concentration, and increasing heating value. For instance, EBFP produced 56.0% WC for GTS, 58.4% for ADS, and 69.6% for DBS when current density was 41.1, 42.1, and 17.9 A/m2, respectively, and a cationic coagulant was dosed at 0.36% on dried solid, 0.46%, and 0.19%, respectively. Without the addition of electricity, the system achieved only 74.3% WC for GTS, 72.8% for ADS, and 74.7% for DBS. Therefore, EBFP would produce a proper cake WC by simply controlling the current density, depending on the destination of dewatered cake such as land application, compost, or incineration."

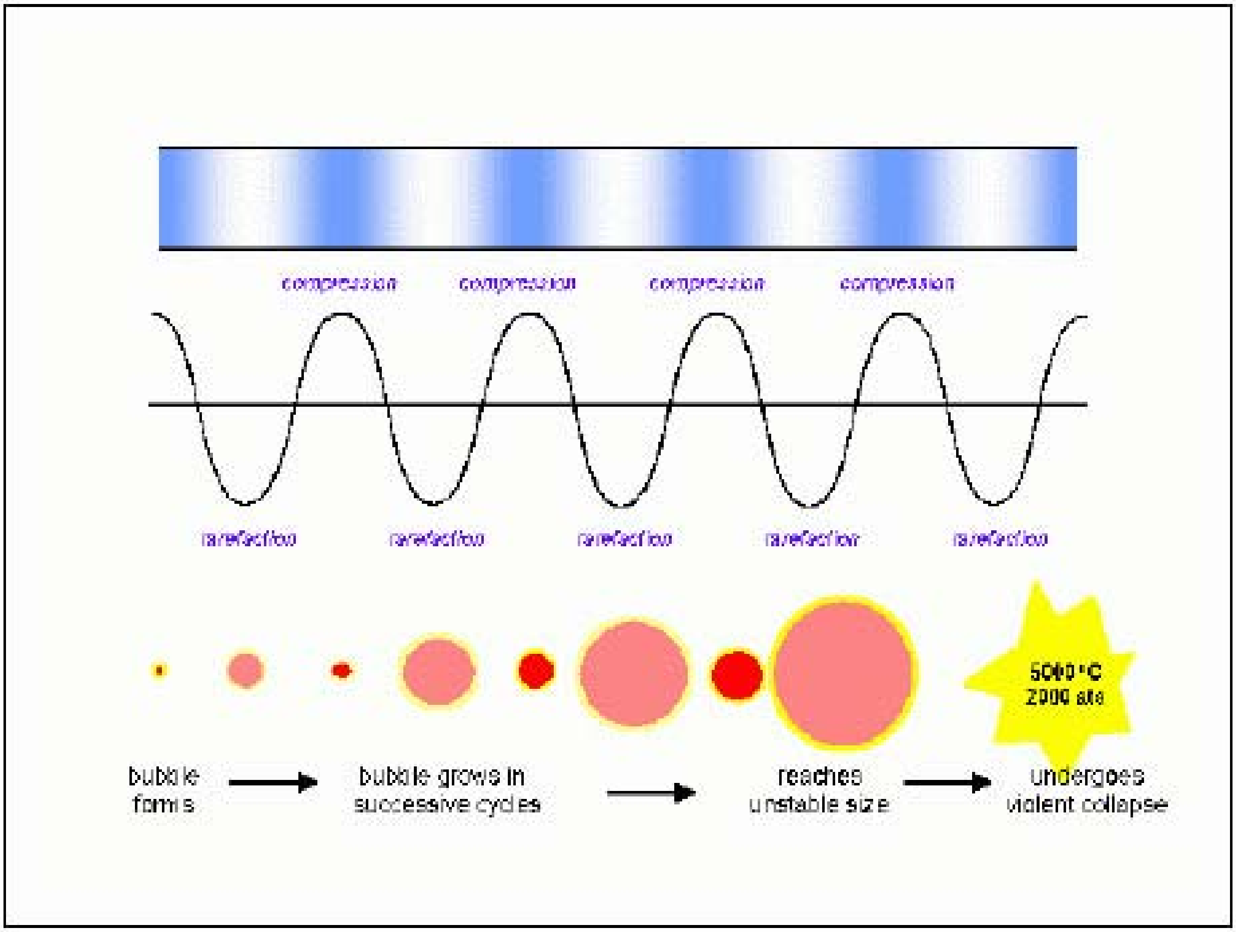
Costs for electrodewatering in a belt filter press are higher than the costs for standard belt filter presses [1]. With continued process and equipment improvements, however, it is possible that costs could become comparable to belt filter presses because the process is only a slight modification on belt filter presses. On the other hand, in applications where the dewatered sludge is transported off-site in trucks, the cost picture is dominated by tipping fees (the cost of hauling and disposal), which are on the order of $100 per dry ton of sludge at 20% solids. If electrodewatering is used to increase the solids content to 40%, the tipping fees per dry ton is automatically reduced by half to around $50 per dry ton.

Table 2–2
Contact Information for Electro-Dewatering of Sludge in a Belt Filter Press

	Contact Information
Contact Name	
Organization	Waste Technologies of Australia, Environmental Biotechnology CRC Pty Ltd, Everleigh, NSW, Australia
Telephone	+61-2-9209-4963
E-mail Address	

Electrohydraulic Cavitation Induced By Ultrasonic Irradiation (Sonolysis)

Ultrasound transducers of sufficient power cause cavitation in liquids. Figure 2–2 illustrates how the ultrasound amplifies the size of the cavitation bubbles over time until they collapse. Collapsing cavitation bubbles result in extremely high pressures (2,000 times atmospheric pressure) and temperatures over 5,000 °C, but only for a brief moment.



Source: ESWE-Institute for Water Research and Water Technology

Figure 2–2
Industrial Electric End-Use Estimates, 2004

The destruction of impurities in the liquid with sound waves is called sonolysis (sonolysis is the breaking of chemical bonds or formation of radicals using ultrasound). The technique is also used to treat heart disease). Electrohydraulic cavitation induced by ultrasonic irradiation is one such means to accomplish sonolysis (spark gaps, impellers, and jet pumps might also work). Higher frequencies of sound waves do not penetrate as far into the liquid as lower frequencies, but higher frequencies cause greater free radical formation [3]. Since the cavitation bubbles tend to form at the impurities, the collapsing cavitation bubbles causes the greatest effect at the impurities: redox reactions and possibly disinfection. The high pressures alone in the collapsing cavitation bubbles can destroy pathogen cells (physically crushing them) [3]. Possible applications include decomposing PCBs, recovering oils from soils, degrading toxic wastes, reaction with water-based pollutants, and perhaps disinfection. Competing mechanical methods to produce cavitation, such as impellers and jet pumps, may be able to produce similar results to ultrasound irradiation but use less electric power.

Electrohydraulic cavitation induced by ultrasonic irradiation as an innovative technology for conditioning biosolids [6]. EIMCO Water Technologies has developed a Sonolyzer™ Ultrasound Unit that ultrasonically generates cavitation micro bubbles in biomass being fed to digesters. They claim that, within the treated waste activated sludge, the agglomerates of microorganisms are impacted and the flocculants are broken down, thus eliminating adequate surfaces for foaming to occur. The result is a disintegrated biomass, which minimizes sludge disposal and makes the ensuing digestion process more efficient.

EIMCO partnered with Sonico LLC (Seal Beach, California) to demonstrate this technology for the Orange County Sanitation District (Fountain Valley, California) [6]. Based on the California demonstration, the approximate capital cost is $265,000 and the approximate O&M costs are $10,000 to $20,000 per year for a 5 to 8 million gallon per day facility treating 30% of the sludge produced per day. It is not clear whether the cost and energy savings in other parts of the plant resulting from sonolysis can recover the added costs and energy consumption of the sonolysis unit.

On the international scene, full-scale sonolysis technology has been demonstrated at the Bad Bramstedt Sewage Works (Germany), at Kävlinge, Sweden (in 2002), and at Mangere Wastewater Treatment Plant, New Zealand (in 2005) [6].

Table 2–3
Contact Information for Electrohydraulic Cavitation Induced by Ultrasonic Radiation

	Contact Information
Contact Name	
Organization	EIMCO Water Technologies, Salt Lake City, UT
Telephone	801-526-2342
E-mail Address	info@eimcowater.com

Electrolysis – Electrokinetic In-Situ Remediation of Groundwater and Soil at Hazardous Waste Sites

Electrokinetic in-situ remediation of groundwater and soil at hazardous waste sites is being pursued by various organizations, for various applications. The technologies are based on in-situ applications of low-energy electrical fields, which induce electrokinetic phenomena in soil or tailings, greatly accelerating the contaminant removal rate. At Mississippi State University, they recently demonstrated laboratory-scale treatment of chromated copper arsenate (CCA) contaminated wood waste.

Electrokinetic Ltd (formerly NuGround Ltd), a UK company, is developing an electrokinetic geosynthetic (EKG) technology to significantly reduce the water content of sewage sludge, mine tailings, and other wastes, which in turn simplifies waste management and disposal. To date, they have used EKG to:

- Consolidate super soft clay
- Allow the construction of reinforced soil using clay slurry
- Stabilize a railway embankment
- Dewater sewage sludge
- Control the condition of natural sports turf surfaces
- Dewater construction waste slurries and mine tailings (see Figure 2–3)

Source: Electrokinetic Ltd.

Figure 2–3
Electrokinetics being used to further dewater thickened tailings

Recent work on diamond mine tailings has shown that EKG can achieve highly accelerated settling of tailings with 50% of the final natural settlement occurring during the first 30 seconds of treatment. Research is ongoing and is focusing on the application of EKG to in situ clean up of contaminated land.

Electrokinetic in-situ remediation should offer substantial cost savings. For example, a Texas company has developed a range of efficient in-situ soil and groundwater treatment technologies that can be adapted to a variety of site and contamination characteristics at very low treatment cost ($30 - $100 per m^3 of soil) and with extremely low energy consumption (20-50 kWh per m^3 of soil [1]. Current technologies, such as incineration or storage at landfills, require excavation and transportation of contaminated soil or water, which results in much higher costs of $400 – $1,000 per m^3 of soil [1]. Comparable energy savings are achieved due to reduction of fuel used for excavation equipment and transportation fuel.

Table 2–4
Contact Information for Electrokinetic In-Situ Remediation of Groundwater and Soil

	Contact Information
Contact Name	R. Mark Bricka
Organization	Mississippi State University, Mississippi State, MS 39762
Telephone	662-325-1615
E-mail Address	bricka@che.msstate.edu
Contact Name	David Huntley
Organization	Electrokinetic Ltd, Newcastle upon Tyne, UK
Telephone	+44 (0)191 243 0685
E-mail Address	david.huntley@electrokinetic.co.uk
Web site	http://www.electrokinetic.co.uk

Supercritical Water Oxidation

When the temperature and pressure of water is brought above its critical point (where the pressure equals 22.1 MPa (3,191 psi) and temperature equals 374°C), water exhibits unique characteristics, many of which are particularly advantageous for environmental treatment. The solubility of organic substances and oxygen into water is significantly increased. Supercritical water oxidation (SCWO) technology takes advantage of this characteristic to completely decompose organic substances. This technology produces a high-quality effluent and is capable of producing Class A biosolids. SCWO also may be referred to as “hydrothermal oxidation.”

SCWO is a promising method for industrial wastewater treatment [2], and an emerging technology that takes advantage of these properties to effect waste treatment [1]. SCWO is also an innovative method for thermal conversion of biosolids; there are ongoing efforts to apply the process in industrial and wastewater treatment facilities [6]. HydroProcessing LLC demonstrated this technology at Harlingen Water Works System (Harlingen, Texas) [6]. The first two units were installed at the Harlingen wastewater treatment facility in July 2001 for use in a pilot study.

Frisch gives the most complete estimate of anticipated costs for SCWO technology [9]. He based his estimate on a hypothetical plant capable of treating 4 gpm (15 lpm) of a waste stream containing approximately 10% organic content by weight. He estimated that the capital costs would be $2,823,000 and annual operating and maintenance costs would be $358,000. These costs translated into a range of $ 0.20 to $ 0.30 per gallon ($0.053 to $0.079 per liter). A Texas company currently using a full-scale supercritical water oxidation system has calculated its costs as $ 0.37 per gallon. These costs compare favorably with at least one conventional alternative, off-site incineration, which costs between $ 0.80 and $ 1.00 per gallon

Although these cost numbers assume a ten-year useful equipment life on any SCWO system, that life may be excessively optimistic. Corrosion is proving to be the most significant obstacle toward more widespread use of this technology. If it can be shown that adjusting the pH in the reactor using certain chemicals can control corrosion rates, the obstacle becomes developing pH monitors capable of operating in the harsh environment of a SCWO reactor.

Table 2–5
Contact Information for Supercritical Water Oxidation

	Contact Information
Contact Name	Jimmy Griffith
Organization	HydroProcessing LLC, Austin, TX
Telephone	512-339-9981
E-mail Address	info@hydroprocessing.com

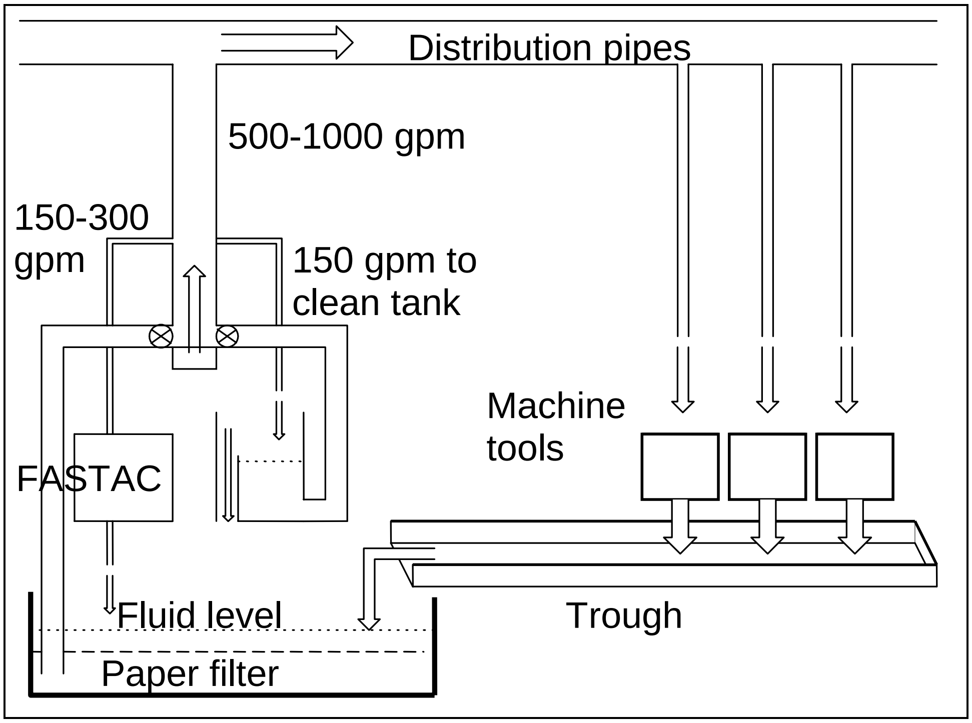
UV Disinfection with Monochromatic Lamp

UV disinfection applies powerful monochromatic ultraviolet light to kill the pathogens in all types of wastewater or recycled liquid streams. Industrial applications include treatment of metal removal fluids, sterilizing pharmaceutical and medical products, etc.

Triton Thalassic Technologies, Inc. (Triton) has developed a high-flow (300 gpm) disinfection system using monochromatic UV light to disinfect nearly opaque fluids such as metal removal fluids [10]. Figure 2–4 shows the location of their FASTAC system in the flow loop for metal removal fluid; only a portion of the flow is processed, but that is sufficient to control the pathogen levels in the storage tank. The UV light destroys pathogens, spores, fungi, and yeasts, reducing concentrations by as much as five orders of magnitude. The system was demonstrated on metal removal fluids at a Volvo plant in Sweden in 2000. Triton sold several systems to GM in 2001.

The number of lamps and the size of the reactors vary by application, but the basic design of the FASTAC™ stays the same. The more opaque and contaminated the fluid is, the more time it needs to spend in the reactors flooded with UV light. The capacity of the FASTAC™ system is measured in gallons per minute (gpm). The design capacity of each system depends upon the following variables:

- MRF sump size
- MRF flow rate
- Level of contamination of the MRF in the sump
- Opacity of the MRF to the UV light

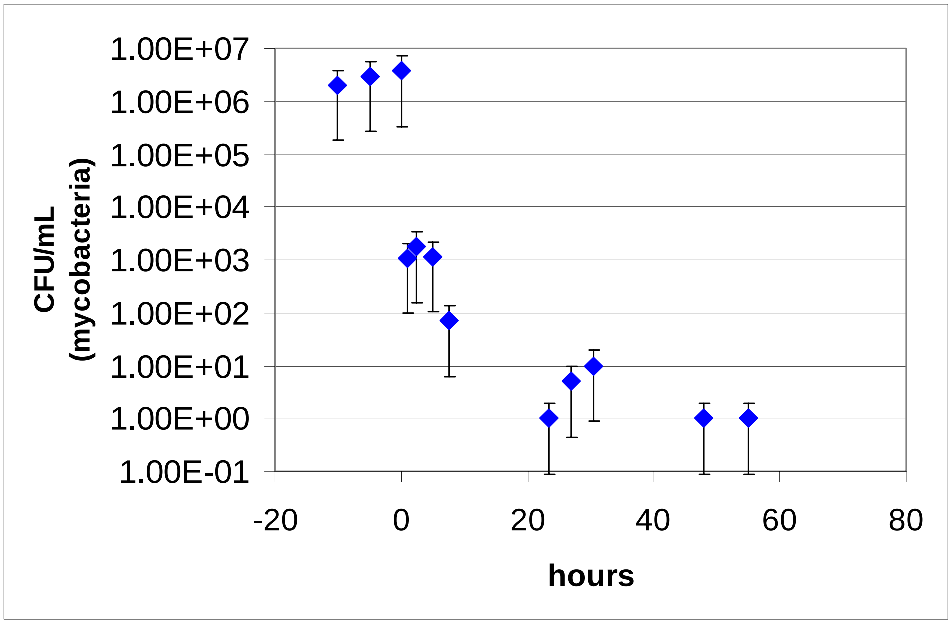


Source: Triton Thalassic Technologies

Figure 2–4
Triton's FASTAC System in the Flow Loop for Metal Removal Fluid

The FASTAC™ system greatly reduces the need for chemical biocides yet still preserves the targeted MRF performance parameters: lubricating, cooling, and inhibiting corrosion. FASTAC™ extends the time between fluid dumps, and the average pathogen levels are 100 to 1000 times lower using FASTAC™. The efficacy of the system was demonstrated in automotive power train plants to reduce bacterial levels by 99.999+%. In field-based microbiology analyses, as illustrated in Figure 2–5, the FASTAC™ system was shown to reduce mycobacteria levels from a high of $5x10^6$ to less than 10 CFU/ml after a day. Test results also showed other bacteria levels dropping from a high of $3x10^8$ to less than $3x10^6$ CFU/ml; and from a high of $5x10^5$ to less than $1x10^3$ CFU/ml after ~5 days.

The capital cost of Triton's FASTAC™ system is approximately $150,000, and they anticipate operating cost of $0.077 per 1000 gallons of MRF treated. These costs correspond to a FASTAC™ system with two 8-kW UV lamps and reactors, designed for a flow rate of 350 gpm (capacity of 500,000 gallons per day) of MRF, and an initial bacterial concentration of 10^7 CFU/mL. Assuming a representative cost of electricity is 10 cents per kWh, the energy cost is only $1.60 per hour.



Source: Triton Thalassic Technologies, Inc.

Figure 2–5
Sample test results for mycobacteria levels

More recently, Triton has pursued the pharmaceutical industry (e.g., sterilizing contact lens), medical industry (blood sterilization), and the food and drink industry (e.g., sterilizing fruit drinks and bottles). Triton recently announced that they had demonstrated the non-thermal sterilization of packaged contact lenses and was seeking FDA approval of this application. The FASTAC™ system is also applicable to a variety of other situations where fluids need to be sterilized. Attractive applications include:

- Pathogen control in complex fluids
- Ultra-pure water systems
- Water for injection (WFI) systems
- Viral clearance of bio-pharmaceuticals and transfusable blood products

In addition, Triton is exploring non-fluid applications of their monochromatic UV sterilization process, including:

- Directed chemical synthesis
- Rapid modification of surface characteristics
- Surface curing
- Food and packaging disinfection
- Light activated medicine

Table 2–6
Contact Information for UV Disinfection with Monochromatic Lamp

	Contact Information
Contact Name	Kevin Kurz
Organization	Triton Thalassic Technologies, Inc., Ridgefield, CT
Telephone	203-438-0633
E-mail Address	kkurz@T3I-uv.com

3
SUMMARY

The goal of this project was to evaluate promising environmental technologies for industrial waste treatment. A wide variety of industrial and waste treatment technologies were reviewed, along with some closely related competing technologies. Advanced technologies for industrial waste treatment work in a variety of ways, including:

- Oxidize the pathogens, VOCs, etc.
- Alter the DNA of the pathogens to neutralize them, destroy them, or to prevent reproduction
- Crush the pathogens in a physical sense
- Cause agglomeration into large particles and filter them or allow them to settle
- Cause chemical reactions which result in phase change, which allow easy separation

A total of 53 advanced technologies applicable to industrial waste treatment were identified. Most of these technologies offer process cost savings and process improvements over existing technologies, yet these technologies have not generally been widely adopted by industry. The adoption barriers typically include one or more of the following:

- High capital cost of advanced technologies
- Reluctance to disrupt a functioning industrial process
- Lost revenues from lower production during conversion process, which includes tuning the entire plant to optimize production with the new equipment
- High cost of certification and approvals (e.g., FDA for pharmaceutical industry and food and drink industry)

From the list of 53 advanced technologies for industrial waste treatment, EEA prepared a short list of promising technologies using the following screening criteria:

- Must be promising electrotechnology not yet established
- Must be applicable to industrial waste treatment (but technologies having other applications were not excluded)
- Must be ready for industrial waste treatment demonstration (beyond an emerging technology, could be a commercially available technology for other applications, could be a commercially available technology for waste treatment in other countries, could have been previously demonstrated for waste treatment in U.S.)

The results of this screening yielded six industrial waste treatment technologies:

- Advanced oxidation process – Photo-oxidation ($UV/O_3/H_2O_2$)
  - Combination is powerful method of oxidative destruction of organics
  - Optimum proportions of UV, O_3, and H_2O_2 for each type of waste stream must be determined experimentally
  - Demonstrated at laboratory and commercial sites

  - At least one supplier
- Electrodewatering in belt filter presses
  - Patented method to increase rate and extent of moisture reduction in belt filter press
  - Demonstrated on sludge at wastewater treatment plant
  - Being pursued by UK company
- Electrohydraulic cavitation induced by ultrasonic irradiation (sonolysis)
  - High pressures and temperatures in collapsing cavitation bubbles physically destroys pathogen cells
  - Full-scale demonstration in Germany, and pilot demonstration at wastewater treatment plant in U.S.
- Electrolysis – Electrokinetic in-situ remediation of groundwater and soil at hazardous waste sites
  - Low-energy electrical fields induce electrokinetic phenomena in soil or tailings, greatly accelerating the contaminant removal rate
  - UK company has used technology to dewater construction waste slurries and mine tailings
- Supercritical water oxidation
  - High-pressure (3,200 psi) and moderately high temperature (700-1,000 °F) oxygenated water completely decomposes organics
  - Pilot demonstration at wastewater treatment plant in U.S.
- UV disinfection using monochromatic lamp
  - Applicable to nearly opaque fluids such as metal removal fluids
  - Also being pursued for sterilizing contact lens packages, blood sterilization, and sterilization of fruit drinks and bottles
  - Reduces pathogen concentrations by 3-5 orders of magnitude
  - Demonstrated at Volvo plant in Sweden and at GM plant in U.S.
  - Recommended for documentation in an EPRI TechApplication

A
ADVANCED INDUSTRIAL WASTE TREATMENT TECHNOLOGIES

Table A-1 is a list of 53 industrial waste treatment technologies considered. Closely related competing technologies using fossil fuels are mentioned.

Table A–1
Potential and Existing Industrial Technologies for Industrial Waste Treatment

Description	Type	Comment
Activated carbon adsorption – Vapor phase	Industrial electrotechnology applicable to waste treatment	Potential for wide-spread use
Activated carbon adsorption with electrical regeneration (Electrosolv®)	Industrial electrotechnology applicable to waste treatment	Demonstrated
Advanced oxidation processes – Catalytic oxidation	Industrial electrotechnology applicable to waste treatment	Potential for wide-spread use
Advanced oxidation processes – $O_3 + H_2O_2$	Industrial electrotechnology applicable to waste treatment	Well-established
Advanced oxidation processes – O_3 at elevated pH	Industrial electrotechnology applicable to waste treatment	Well-established
Advanced oxidation processes – Photo-oxidation ($UV/O_3/H_2O_2$)	Industrial electrotechnology applicable to waste treatment	Well-established in other applications
Advanced oxidation processes using catalyst and electrodes doped with elemental Nb or Ta	Industrial electrotechnology applicable to waste treatment	Bench tested
Air flotation – Bubble assisted flotation	Industrial electrotechnology applicable to waste treatment	Commercially available

Description	Type	Comment
Air flotation -- Conventional	Industrial electrotechnology applicable to waste treatment	Well-established
Air flotation -- Ozonated	Industrial electrotechnology applicable to waste treatment	Untested concept
Biological treatment (anaerobic digestion with ozone treatment)	Industrial electrotechnology applicable to waste treatment	Bench tested
Dielectric heating system using microwaves	Industrial electrotechnology applicable to waste treatment	Bench tested
Dielectric heating system using radio waves	Industrial electrotechnology applicable to waste treatment	Field tested but commercially available for other applications
Electro-acoustic dewatering in belt filter press	Industrial electrotechnology applicable to waste treatment	Bench tested
Electro-dewatering in belt filter press	Industrial electrotechnology applicable to waste treatment	Bench tested
Electrohydraulic cavitation induced by spark-gap discharge (lithotripsy)	Industrial electrotechnology applicable to waste treatment	Well-established in medical applications
Electrohydraulic cavitation induced by ultrasonic irradiation (sonolysis)	Industrial electrotechnology applicable to waste treatment	Preliminary research (including EPRI demonstration 10 years ago)
Electrolysis – Cerium-catalyzed electrochemical oxidation process (CerOx®)	Industrial electrotechnology applicable to waste treatment	Was under development
Electrolysis – Electro-coagulation (conventional)	Industrial electrotechnology applicable to waste treatment	Well-established
Electrolysis – Electro-coagulation using stainless steel cathodes and iron anodes	Industrial electrotechnology applicable to waste treatment	Bench tested

Description	Type	Comment
Electrolysis – Electrokinetic in-situ remediation of groundwater and soil at hazardous waste sites	Industrial electrotechnology applicable to waste treatment	Small-scale demonstrations in the field
Electron beam irradiation to accelerate oxidation	Industrial electrotechnology applicable to waste treatment	Under development
Electro-osmotic dewatering	Industrial electrotechnology applicable to waste treatment	Bench-scale tested for environmental applications but commercially available for other applications
Electrostatic precipitation	Industrial electrotechnology applicable to waste treatment	Well-established
Freeze concentration / crystallization	Industrial electrotechnology applicable to waste treatment	Pilot-scale tested (including numerous EPRI demonstrations)
Heat pump evaporation	Industrial electrotechnology applicable to waste treatment	Well-established
Incineration – Electrically heated flameless VOC oxidizer	Industrial electrotechnology applicable to waste treatment	Commercially available
Incineration -- High-temperature fluid wall reactor (resistance heating)	Industrial electrotechnology applicable to waste treatment	Preliminary research
Incineration – Induction heating	Industrial electrotechnology applicable to waste treatment	Preliminary research
Incineration – IR furnace	Industrial electrotechnology applicable to waste treatment	Well-established
Incineration – Molten-glass furnace (resistance heating)	Industrial electrotechnology applicable to waste treatment	Well-established
Incineration – Plasma or electric-arc heating	Industrial electrotechnology applicable to waste treatment	Well-established

Description	Type	Comment
Incineration – Pyrolytic incinerator (resistance heating)	Industrial electrotechnology applicable to waste treatment	Preliminary research
Infrared drying using electric IR emitters	Industrial electrotechnology applicable to waste treatment	Under development
Ion exchange – Resin (conventional)	Industrial electrotechnology applicable to waste treatment	Well-established
Ion exchange – Resin for selective ion recovery	Industrial electrotechnology applicable to waste treatment	Bench tested
Low-temperature (non-thermal) plasmas	Industrial electrotechnology applicable to waste treatment	Under development
Membrane separation – Electrodialysis with bipolar membranes	Industrial electrotechnology applicable to waste treatment	Promising
Ozonation (conventional ozone oxidation)	Industrial electrotechnology applicable to waste treatment	Well-established
Ozonation for control of NOx in stack gases	Industrial electrotechnology applicable to waste treatment	Preliminary research
Ozonation for processing rubber from scrap tires	Industrial electrotechnology applicable to waste treatment	Under development
Photocatalysis with UV + TiO_2	Industrial electrotechnology applicable to waste treatment	Preliminary research
Photocatalytic oxidation using specific wavelengths of light	Industrial electrotechnology applicable to waste treatment	Well-established
Plasma arc furnace for high-temperature plasma processing	Industrial electrotechnology applicable to waste treatment	Demonstrated, some types are commercially available

Description	Type	Comment
Plasma-assisted sludge oxidation	Industrial electrotechnology applicable to waste treatment	Bench tested
Refrigerated vapor condensation	Industrial electrotechnology applicable to waste treatment	Well-established
Regenerated hydrophobic polymer sorbent for VOC control (electric powered)	Industrial electrotechnology applicable to waste treatment	Demonstrated in 1996
Supercritical water oxidation	Industrial electrotechnology applicable to waste treatment	Preliminary research
Thermal hydrolysis	Industrial electrotechnology applicable to waste treatment	Commercially available
UV disinfection – Monochromatic lamp	Industrial electrotechnology applicable to waste treatment	Under development
UV radiation – Broad-band lamp	Industrial electrotechnology applicable to waste treatment	Well-established
Vacuum pyrolysis (Pyrocycling™)	Industrial electrotechnology applicable to waste treatment	Under development
Wet air oxidation	Industrial electrotechnology applicable to waste treatment	Well-established

The sections below provide a brief introduction to each technology.

Activated Carbon Adsorption – Vapor Phase

Activated carbon adsorption of liquid waste streams is a well-established environmental treatment [1]. The contaminated activated carbon is normally regenerated with heat in a furnace fired by natural gas or another fossil fuel. The heat volatilizes the pollutants from the activated carbon.

Vapor phase activated carbon adsorption is a promising method for industrial air pollution control [2]. The activated carbon is regenerated using steam. About a quarter of the energy used for regeneration comes from electricity.

This is an emerging industrial electrotechnology that is applicable to industrial waste treatment.

Activated Carbon Adsorption with Electrical Regeneration (Electrosolv®)

Electrosolv® is a patented process for regenerating granular activated carbon (GAC) [1]. GAC is widely used to remove VOCs in water and air from industrial processes. The VOCs are adsorbed until the pores of the carbon are full and no further adsorption can take place. GAC is conventionally regenerated by heating the carbon to a temperature of 150-200 °C and by purging the bed with gas. GAC can be regenerated using steam, an inert gas, or thermally. In each case, VOCs are released and flushed away during the regeneration process. The Electrosolv® process regenerates the GAC by heating the carbon using an electric potential across electrodes placed at each end of the GAC bed. The GAC is an electrical resistor, so the carbon can be heated directly, and varying the voltage can control temperature. A relatively pure VOC stream is driven off from the carbon, and can be removed by vacuum, or a small flow of purge gas, and condensed for reuse or disposal.

This is an emerging industrial electrotechnology that is applicable to industrial waste treatment.

Advanced Oxidation Processes – Catalytic Oxidation

Catalytic oxidation is a promising advanced oxidation process for industrial air pollution control [2].

This is an emerging industrial electrotechnology that is applicable to industrial waste treatment.

Advanced Oxidation Processes – O_3 + H_2O_2

Advanced oxidation processing using ozone, UV, and hydrogen peroxide are well established and, in most cases, commercially available for industrial processes [1]. However, advanced oxidation processes using ozone and hydrogen peroxide are promising methods for industrial wastewater treatment [2].

This is an industrial electrotechnology that is applicable to industrial waste treatment.

Advanced Oxidation Processes – O_3 at Elevated pH

Advanced oxidation processing using ozone, UV, and hydrogen peroxide are well established and, in most cases, commercially available for industrial processes [1]. However, advanced oxidation processes using ozone at elevated pH levels are promising methods for industrial wastewater treatment [2].

This is an industrial electrotechnology that is applicable to industrial waste treatment.

Advanced Oxidation Processes – Photo-Oxidation (UV/O_3/H_2O_2)

Advanced oxidation processing using ozone, UV, and hydrogen peroxide are well established and, in most cases, commercially available for industrial processes [1]. However, advanced oxidation processes using photo-oxidation combining UV radiation with ozone and hydrogen peroxide are promising methods for industrial wastewater treatment [2].

Jensen reports that an advanced oxidation process using UV and H_2O_2 is used for groundwater remediation to provide drinking water in small communities [3]. He also reports that advanced oxidation processes using UV and O_3 are used for EPA site cleanup as well as groundwater remediation to provide drinking water in small communities. In particular, Jensen has demonstrated the use of ozone as effective at oxidizing metal cyanide complexes such as $Fe(CN)_6$ generated in copper and cadmium plating processes.

This is an emerging industrial electrotechnology that is applicable to industrial waste treatment.

Contact: Dr. James N. Jensen, University of Buffalo, Buffalo, NY, 716-645-2114 x2329, jjensen@eng.buffalo.edu.

Advanced Oxidation Processes Using Catalyst and Electrodes Doped With Elemental Niobium or Tantalum

Advanced oxidation processes using catalyst and electrodes doped with elemental niobium or tantalum had been bench tested [1]. This technology is a method to produce hydroxyl free radicals that may be more efficient and less costly to operate than conventional oxidation methods. This technology is applicable to municipal water plants, municipal wastewater plants, auto plants, removal of organics from water, oxidation of heavy metals and taste and odor-causing compounds, treatment of landfill leachate, and for tertiary treatment in water reuse schemes. Michael R. Hoffman at CalTech led the original research effort.

This is an emerging industrial electrotechnology that is applicable to industrial waste treatment.

Contact: Michael R. Hoffman, CalTech, Pasadena, CA, 626-395-4391, mrh@caltech.edu.

Air Flotation – Bubble Assisted Flotation

EPRI reports that bubble assisted flotation provides for more efficient separation [1].

This is an emerging industrial electrotechnology that is applicable to industrial waste treatment.

Air Flotation -- Conventional

Dissolved air flotation is a common separation process, particularly in industrial wastewater treatment [1]. Dissolved air flotation is a treatment process removes suspended matter such as oil or solids that is achieved by dissolving air in the water or wastewater under pressure and then releasing the air at atmospheric pressure in a flotation tank or basin. The released air forms tiny bubbles that adhere to the suspended matter, causing the suspended matter to float to the surface where it is removed by a skimming device. Dissolved air flotation is very widely used in treating the industrial wastewater effluents from oil refineries, petrochemical and chemical plants, natural gas processing plants and similar industrial facilities.

This is an industrial electrotechnology that is applicable to industrial waste treatment.

Air Flotation -- Ozonated

Jensen suggested adding ozone to the air before it is released in the tank to oxidize some of the contaminants [3]. A pressurized tank would decrease the electrical load by allowing for recycling of the air and the remaining ozone.

This is an emerging industrial electrotechnology that is applicable to industrial waste treatment.

Biological Treatment (Anaerobic Digestion with Ozone Treatment)

Anaerobic digestion with ozone treatment is an embryonic technology for stabilization of biosolids [6]. Vranitsky and Lahnsteiner demonstrated the benefit of adding low levels of ozone to anaerobically digested biosolids, which increased the degradation rate of organic matter and also increased the biogas production due to the added biological disintegration from the ozone addition [11].

This is an emerging industrial electrotechnology that is applicable to industrial waste treatment.

Contact: American Air Liquide, Houston, TX, 800-820-2522.

Dielectric Heating System Using Microwaves

Dielectric heating systems is promising methods for industrial solid waste management [2].

EPRI reports, "In the dielectric heating process, an alternating electric field of high frequency is used to generate heat in non-conductive or dielectric materials, such as water. Both radio frequencies (RF) and microwave frequencies are used. Microwaves are used commercially in many industrial applications, such as curing rubber and in drying various coatings, but have been applied only sparingly to environmental problems [1]."

At one time, someone (probably Dr. Faiz Pourarian) at a laboratory affiliated with Carnegie Mellon University performed bench tests using microwaves for dielectric heating of oily steel mill sludge, with the hope of greatly reducing disposal costs. The microwave process removed over 95% of oil and grease from the sludge. The technology might be useful to reduce the amount of sludge processed by conventional oil-water separators.

This is an industrial electrotechnology that is applicable to industrial waste treatment.

Contact: Jeanne VanBriesen, CMU, Pittsburgh, PA, 412-268-4603, jeanne@cmu.edu.

Direct microwave drying is an innovative technology for drying biosolids [6]. Burch BioWave® is a patented continuous flow process that uses a multi-mode microwave system to remove moisture and pathogens from dewatered sludge. The BioWave unit also forces air heated by gaseous fuel (e.g., natural gas, LPG, or digester gas) through the biosolids to help evaporate the moisture released by the microwaves.

This is an industrial electrotechnology that is applicable to industrial waste treatment.

Contact: Burch Hydro, Inc., Fredricktown, OH, 800-548-8694

Dielectric Heating System Using Radio Waves

Dielectric heating systems is promising methods for industrial solid waste management [2].

EPRI reports that "in the dielectric heating process, an alternating electric field of high frequency is used to generate heat in non-conductive or dielectric materials, such as water. Both radio frequencies (RF) and microwave frequencies are used [1]."

PSC (Cleveland, Ohio) has developed radio frequency (RF) drying equipment that could be applied to wastewater treatment. Ben Wilson at PSC reports that PSC has done medical waste sterilization by heating a flowing liquid in a tube to 98-100 °C, but PSC has not found a niche market for RF in industrial waste treatment. PSC has determined that RF drying is not cost effective for high volumes of water. Other technologies, such as either electric or gas IR heating, centrifuge, microwave heating, fluid bed dryer, and drum dryer, are much more cost effective. RF drying is, however, cost effective for high value products where manufacturers can replace batch processes with drying times of 12-24 hours to continuous processes with drying times of 30-90 minutes. RF drying might also be the best option when the product to be dried cannot be exposed to the atmosphere and is in powder form at the completion of the drying process (e.g., radioactive waste).

This is an emerging industrial electrotechnology that might be applicable to industrial waste treatment.

Contact: PSC, Cleveland, Ohio, 800-538-1337, info@pscrfheat.com.

Electro-acoustic Dewatering in Belt Filter Press

Electro-acoustic dewatering is an embryonic method for dewatering biosolids [6]. The combination of electric field and ultrasound waves can enhance dewatering by around 10% over conventional dewatering, to a final solids concentration up to 29%. In bench-scale studies by Battelle Laboratories, electro-acoustic dewatering was shown to decrease specific energy consumption, increase the filtration rate, and help keep the cathode clean.

Contact: OilTrap Environmental, Tumwater, WA, 360-943-6495, support@oiltrap.com.

Electrodewatering in Belt Filter Press

Electro-dewatering of sludge in a belt filter press increases the rate and extent of moisture reduction. When a DC voltage is imposed on the sludge, the electro-osmotic driving force increases the solids content of municipal wastewater sludge from ~20% to over 40% solids [1]. The technology should be applicable to pulp and paper mills and steel mills. Electrodewatering is an innovative method for dewatering biosolids [6]. The electric field causes electrophoresis at the initial stages, and, once a cake is formed, electro-osmosis.

Contact: Patricia Hurtado, Global Energy Partners, Lafayette, CA, 925-284-3780, phurtado@gepllc.com; Keith Carns, kcarns@gepllc.com.

Contact: Waste Technologies of Australia, Environmental Biotechnology CRC Pty Ltd, Everleigh, NSW, Australia +61-2-9209-4963.

Electrohydraulic Cavitation Induced by Spark-Gap Discharge (Lithotripsy)

This technology uses electrical energy to induce cavitation (i.e., the formation and collapse of small vapor bubbles) in a water sample [1]. The processes leading to cavitation produce shock waves and lead to the release of high-energy light. Collapsing cavitation bubbles result in extremely high pressures and temperatures for a brief moment – temperatures over 5,000 °C are quoted by Jensen [3]. During cavitation, various reactive species are formed, including hydroxyl radicals, hydrogen atoms, and hydrogen peroxide. Since the cavitation bubbles tend to form at the impurities, the collapsing cavitation bubbles causes the greatest effect at the impurities. Jensen reports that simply the high pressures in the collapsing cavitation bubbles can destroy pathogen cells.

Electrohydraulic cavitation can be induced using a spark-gap discharge in water. Lithotripsy is the term used to describe the breaking of kidney stones by using an externally applied, focused, high-intensity acoustic pulse.

Electrohydraulic Cavitation Induced By Ultrasonic Irradiation (Sonolysis)

Ultrasound transducers of sufficient power cause cavitation in liquids. The destruction of impurities in the liquid with sound waves is called sonolysis. Electrohydraulic cavitation induced by ultrasonic irradiation is one such means to accomplish sonolysis. Collapsing cavitation bubbles result in extremely high pressures and temperatures for a brief moment – temperatures over 5,000 °C are quoted by Jensen [3]. Higher frequencies do not penetrate as far into the liquid as lower frequencies, but higher frequencies cause greater free radical formation. Since the cavitation bubbles tend to form at the impurities, the collapsing cavitation bubbles causes the greatest effect at the impurities: redox reactions and possibly disinfection. Jensen reports that simply the high pressures in the collapsing cavitation bubbles can destroy pathogen cells. Possible applications include decomposing PCBs, recovering oils from soils, degrading toxic wastes, reaction with water-based pollutants, and perhaps disinfection. Competing mechanical methods to produce cavitation, such as impellers and jet pumps, may be able to produce similar results to ultrasound irradiation, but use less electric power.

Contact: James Jensen, University of Buffalo, Buffalo, NY, 716-645-2114, x2329, jjensen@eng.buffalo.edu.

Parsons describes this as an innovative technology for conditioning biosolids [6].

Contact: EIMCO Water Technologies, Salt Lake City, UT, 801-526-2342, info@eimcowater.com.

Electrolysis – Cerium-Catalyzed Electrochemical Oxidation Process (CerOx®)

Cerox Corporation was developing a technology to convert hazardous organic waste streams (such as biogenic wastes, toxic chemicals, pesticides, herbicides, PCBs, and dilute organics in water) into CO_2 and water.

Contact: CerOx Corporation, Sunnyvale, CA, 408-744-9180.

Or: Norvell Nelson, CerOx Corporation, Santa Maria, CA, 805-925-9355, njnelson@cerox.com.

Electrolysis – Electro-coagulation (Conventional)

Electrocoagulation is an electrolysis method for industrial wastewater treatment [2]. This process is well-established, and is fairly common in industry, since it avoids the use of additional chemicals to remove solids from a process stream [1].

Parsons describes an embryonic biosolids conditioning technology using a sacrificial aluminum anode [6]. The aluminum ions combined with very fine negatively charged ions and particles in suspension to form agglomerations surrounded by gas bubbles that rise to the surface. Parsons also mentions an electrocoagulation technology for domestic wastewater treatment sold by Powell Water Systems, Inc.

Contact: Scott Powell, Powell Water Systems, Inc., Centennial, CO, 303-627-0320, scottpowell@powellwater.com.

Electrolysis – Electro-Coagulation Using Stainless Steel Cathodes and Iron Anodes

Electro-coagulation using stainless steel cathodes and iron anodes in a tubular configuration may increase removal efficiency, reduce cost, and reduce bacterial load. This system has been tested on leachate from mining spoils, landfill leachate, municipal sewage (primary clarifier influent), and lake water for potable uses [1]. This technology may be applicable to removal of contaminants such as turbidity, inorganic, biochemical oxygen demand (BOD), chemical oxygen demand (COD), and oil and grease.

Contact: Shankar Chellan, University of Houston, Houston, TX, 713-743-4265, chellam@uh.edu.

Electrolysis – Electrokinetic In-Situ Remediation of Groundwater and Soil at Hazardous Waste Sites

Electrokinetic in-situ remediation of groundwater and soil at hazardous waste sites is being pursued by various organizations, for various applications. The technologies are based on in-situ applications of low-energy electrical fields, which induce electrokinetic phenomena in soil or tailings, greatly accelerating the contaminant removal rate. At Mississippi State University, they recently demonstrated laboratory-scale treatment of chromated copper arsenate (CCA) contaminated wood waste.

Contact: R. Mark Bricka, Mississippi State University, 662-325-1615, bricka@che.msstate.edu

A UK company is developing an electrokinetic geosynthetic (EKG) technology to significantly reduce the water content of sewage sludge, mine tailings, and other wastes, which in turn simplifies waste management and disposal.

Contact: David Huntley, Electrokinetic Ltd, Newcastle upon Tyne, UK, 0191-243-0685, david.huntley@electrokinetic.co.uk

Electron Beam Irradiation to Accelerate Oxidation

Electron beam irradiation accelerates oxidation and reduction of organic and inorganic compounds in water and wastewater. However, electron beams must be powerful (1-5 MeV) in order to penetrate more than a quarter inch into water. Applications are to remove pollutants from potable water supplies, hazardous waste, medical wastes, wastewater, and metal fabrication shop waste. Tests for combined sewage outflow (CSO) applications showed electron beams to be less effective at reducing bacterial load than ultraviolet irradiation, ozonation, chlorine dioxide disinfection, and chlorination/dechlorination.

Advanced oxidation processes using electron beam irradiation is a promising method for industrial wastewater treatment [2].

Contact: Mary Stinson, U.S. EPA, (732) 321-6683, stinson.mary@epa.gov.

Electro-Osmotic Dewatering

This technology uses an imposed electric field to force ionic constituents to migrate to their attractive electrodes, and that this phenomenon has been successfully used in the ceramics industry for product dewatering, as well as in the construction industry for soil dewatering at building foundations and for migration of friction-decreasing water films to pile surfaces during driving [1].

Electro-osmotic dewatering is an embryonic method for dewatering biosolids [6].

Electro-osmotic dewatering is feasible in removing bound water from agricultural waste and wastewater sludge. Applications include pulp and paper mills, chemical plants, and steel mills. In the agricultural area, as recently as 2005 [12], researchers have recommended that less developed technologies (including electro-osmotic dewatering) "need further research to provide a better understanding of the underlying physics and to assess their ultimate industrial potential."

Contact: Christopher G.J. Baker, Arvatec (UK) Ltd, Wantage, UK and Chemical Engineering Department, Kuwait University, Kuwait.

Electrostatic Precipitation

Electrostatic precipitation is employed widely in the air pollution control field. Stack gases are passed through an electric field to improve the removal of charged particulates. While this technology could benefit from research leading to improved methods, it is commercially established.

Freeze Concentration / Crystallization

When contaminated water is frozen, the water tends to freeze first and drive the impurities into the unfrozen portion. Freezing also alters the chemical bonds between the solids and the water. When the mixture is melted, the concentrated liquid pockets drain out first and conventional sludge dewatering equipment is much more effective on the remaining sludge. This conditioning process can be applied to municipal and industrial sludge, and in the food processing industry. It is especially effective for inorganic (e.g., alum and ferric iron) sludge. EPRI has funded numerous demonstrations of this technology.

Freeze concentration is a viable method for industrial wastewater treatment [2]. Mechanical freeze-thaw is an embryonic method for dewatering biosolids [6].

Heat Pump Evaporation

Heat pumps are a well-established technology in industrial, commercial, and residential applications. The most common industrial application of heat pumping evaporation is dehumidification drying of lumber. In this application, warm, humid exhaust air from a lumber-drying kiln is the heat source for a closed-cycle mechanical heat pump that delivers heat to the incoming air.

The most common large-heat-load application is vapor compression evaporation. In this application, evaporated vapor is compressed over a small pressure range and condensed to provide the energy to drive the evaporation process. Evaporators and flash-steam recovery systems frequently incorporate thermocompression systems. For example, paper dryers commonly use thermocompressors to recover flash steam from dryer condensate.

In industrial waste treatments, heat pump evaporation uses heat pumps in a conventional evaporative process to concentrate polluted waste streams.

Various manufacturers have made significant advancement in heat pump technology, so this technology was not pursued further.

Heat pump evaporation is a method for industrial wastewater treatment [2].

Incineration – Electrically Heated Flameless VOC Oxidizer

Incineration is a waste treatment technology that involves the combustion of organic materials and/or substances. Manufacturing processes that generate volatile organic compounds (VOCs) commonly use fume incineration, which destroys the VOCs through thermal oxidation, which converts the organics into stable and non-toxic compounds such as CO_2 and H_2O for emission to the atmosphere. The heat required to maintain the destruction temperature in the thermal oxidizer can be provided by electric heating or by combusting fossil fuels.

A small electric powered flameless thermal oxidizer (FTO) for destruction of VOC and hazardous air pollutants (HAPs) is commercially available from Selas Fluid Processing, a subsidiary of The Linde Group. The Thermatrix® ES FTO System is electrically heated and designed to treat relatively low flow rates of dilute fume. It handles up to 500 scfm.

Incineration -- High-Temperature Fluid Wall Reactor

Several electric-based technologies are used to incinerate solid, liquid, and gaseous wastes. Incinerators using resistance technology, which are commercially available, are used in high-temperature fluid wall reactors.

Thagard Research Corporation developed high-temperature fluid wall (HTFW) reactors for incineration with resistance heating [13]. J. M. Huber Corporation later bought the technology rights.

Incineration – Induction Heating

An induction furnace uses electromagnetic induction to heat a metal to its melting point. Some Russians have patented the use of induction heating for processing solid mixed waste [14]. When solid mixed waste contains radioactive and hazardous materials, a combination of a plasma torch and induction coils may be effective at converting the waste into separate metallic, slag, and gaseous phases to facilitate disposal. The metallic phase of the waste material and the glass-like, non-metallic slag phase containing radioactive elements are removed separately in the form of ingots. The decomposition products of the organic and toxic materials are incinerated as part of the process.

This is a potential electrotechnology for industrial waste treatment.

Incineration – Infrared Furnace

Infrared furnaces are used to incinerate solid, liquid, and gaseous wastes. Electric infrared incinerators for processing solid waste consist of a horizontally oriented, insulated furnace. A woven wire belt conveyor extends the length of the furnace and infrared heating elements are located in the roof above the conveyor belt. Dewatered sludge cake is conveyed into one end of the incinerator. An internal roller mechanism levels the sludge into a continuous layer approximately one inch thick across the width of the belt. The sludge is sequentially dried and then burned as it moves beneath the infrared heating elements. Ash is discharged into a hopper at the opposite end of the furnace. Hot flue gases may be used to supplement the infrared heating. Combustion air is preheated by the flue gases and is injected into the discharge end of the furnace. The hot flue gases leave the furnace at the feed end. The electric infrared furnace offers the advantage of lower capital cost, especially for smaller systems. Electric infrared incinerator emissions are usually controlled with a venturi scrubber or some other wet scrubber.

Infrared furnaces are a promising method for industrial solid waste management [2].

Incineration – Molten-Glass Furnace

Incineration is a waste treatment technology that involves the combustion of organic materials and/or substances. Manufacturing processes that generate volatile organic compounds (VOCs) commonly use fume incineration, which destroys the VOCs through thermal oxidation, which converts the organics into stable and non-toxic compounds such as CO_2 and H_2O for emission to the atmosphere. The heat required to maintain the destruction temperature in the thermal oxidizer can be provided by electric heating or by combusting fossil fuels.

Several electric-based technologies are used to incinerate solid, liquid, and gaseous wastes. Electric resistance technology, which is commercially available, is used in molten glass incinerators. The heat can also be provided by fossil fuels.

Molten glass furnaces are a promising method for industrial solid waste management [2].

Incineration – Plasma or Electric-Arc Heating

Plasma heating or electric-arc furnaces can be used to incinerate solid, liquid, and gaseous wastes.

Incineration – Pyrolytic Incinerator

Pyrolytic incineration can employ either fossil fuel or resistance heating. Pyrolytic incinerators are a reliable and common treatment process for health-care waste [15]. Incinerators can be used to destroy hazardous wastes, solid wastes, and municipal biosolids.

Infrared Drying Using Electric IR Emitters

Infrared (IR) radiation can be used to dry environmental sludge [1]. IR drying in industrial processes often use fossil fuels, more commonly natural gas. Electric infrared emitters have lower overall capital costs and a higher efficiency, and can reduce gaseous emissions commonly encountered with fossil fuel-driven dryers.

Ion Exchange – Resin (Conventional)

Ion exchange is a method for industrial wastewater treatment [2]. Ion exchange is a common physical-chemical treatment process where specialized resins are used to extract ions from a waste stream [1]. Contaminated water is pumped through the resin so that the harmful ions are exchanged with more benign ones incorporated into the resin. For instance, heavy metals in polluted water can be exchanged for sodium ions. The biggest drawback to existing ion exchange techniques is its non-specificity.

Ion Exchange – Resin for Selective Ion Recovery

One researcher is developing a specialized resin that targets specific contaminants [1]. While ion exchange has limited energy-related issues, the specialized resin is regenerated using a proprietary electrochemical process.

Low-Temperature (Non-Thermal) Plasmas

Low-temperature plasmas are ionized gases generated at ambient temperatures. There is a significantly smaller concentration of reactive species produced in low-temperature plasmas than in high-temperature plasmas. Nonetheless, this technology is suitable for treatment of gaseous waste or relatively clean water [1].

Membrane Separation – Electrodialysis with Bipolar Membranes

The three principal types of membrane separation are microfiltration, ultrafiltration, and reverse osmosis. They differ in the nominal size of the particles that can be removed. Membrane pore sizes can vary from 0.1 nanometer (nm) to 5 micrometer (μm), depending on filter type.

Electrodialysis with bipolar membranes is a membrane separation method for wastewater treatment [2]. Electrodialysis is an electromembrane process in which ions are transported through ion permeable membranes from one solution to another under the influence of a potential gradient. Bipolar membrane electrodialysis efficiently converts aqueous salt solutions into acids and bases without chemical addition. One possible application is to use bipolar membranes to recover fluoride waste in refinery operations [16].

Ozonation (Conventional Ozone Oxidation)

When molecular oxygen (O_2) is passed through an electric current, a portion of the oxygen is converted to ozone (O_3). Ozone is a highly reactive chemical that, under the proper circumstances, leads to advanced oxidation processes.

Ozone oxidation is a promising method for industrial wastewater treatment [2]. The ozone industry is mature worldwide. Many ozone applications in environmental fields are established [1].

Ozonation for Control of NOx in Stack Gases

Ozonation for control of NOx in stack gases is a potential electrotechnology for industrial waste treatment.

Ozonation for Processing Rubber from Scrap Tires

Ozonation for processing rubber from scrap tires is a potential electrotechnology for industrial waste treatment.

Photocatalysis with UV and TiO_2

Photocatalysis is the acceleration of a photoreaction in the presence of a catalyst. Titanium dioxide is an effect catalyst for electrolysis of water. Jensen reports that photocatalysis combining a UV lamp with TiO_2 is an effective method to destroy pathogens by oxidation processes [3].

Contact: Dr. James N. Jensen, University of Buffalo, Buffalo, NY, 716-645-2114 x2329, jjensen@eng.buffalo.edu .

Photocatalytic Oxidation Using Specific Wavelengths of Light

Advanced oxidation processes using photocatalysis are promising methods for industrial wastewater treatment [2]. Oxidation can be accelerated in the presence of certain wavelengths of light to treat wastes in a process termed photocatalytic oxidation [1]. In fact, the combination of UV and ozone to generate advanced oxidation processes (as discussed above) is one form of photocatalytic oxidation. While the kinetics behind this technology are poorly understood, it has been applied to a wide variety of industrial and environmental applications and several vendors are marketing this equipment.

Plasma Arc Furnace for High-Temperature Plasma Processing

High-temperature plasma processing raises the temperature of a solid material to almost 2,000°C. The solid material is sterilized, melted, and oxidized, and upon cooling, becomes a vitrified slag. Applications include removal of difficult organics in solid waste, hazardous wastes, and biological wastes.

Plasma arc furnaces are promising methods for industrial solid waste management [2].

Several related technologies are offered by Foret Plasma Labs that combine a plasma arc and a fluid vortex. The trademarks include Plasma Whirl™, ArcWhirl™, Plasma Whirl ArcLight™, Plasma Arc Curtain™, Carbon WhirlArc UV Light™, and ArcFoam™. Industrial applications claimed by the manufacturer include upgrading heavy oil and oil sands, complete organic cracking, tank bottoms vitrification, drill cuttings melting, oil and water separation, complete organic destruction, pathogen disinfection, wastewater effluent disinfection, benzene in sludge, heavy metals in water, wastewater thickened sludge disinfection, spent caustic treatment, paint booth water disinfection and VOCs, paint booth sludge, foundry sand, metal working fluid mycobacteria contamination, oxidizing unburned carbon on fly ash, medical waste vitrification, oxidizing VOCs, reduce BOD and COD in wastewater, industrial wastewater pretreatment, zero H_2S emissions, recovering base fluid, Class A biosolids, zero odors in metal working fluid, paint booth sludge destruction, zero mycobacteria in metal workings fluid, medical waste destruction, treating spent caustic, produced water and brine evaporation, gray and black water destruction, black liquor gasification, pulp bleaching, and nitrogen trichloride destruction.

Contact: Foret Plasma Labs, LLC, The Woodlands, TX, 281-419-5198, kbwintenburg@plasmawhirl.com.

Plasma-Assisted Sludge Oxidation

Hydro Quebec has extensively tested a moderate-temperature plasma technology. Plasma-assisted sludge oxidation (PASO) using a rotary oven operating at between 500° and 600°C at atmospheric pressure. The PASO technology reduces sludge volumes by 95%. Parsons (2006) describes PASO as being an embryonic method for thermal conversion of biosolids.

Contact: Fabgroups Technologies, Inc., St. Laurent, Québec, 514-331-3712, tmulhern@fabgroups.com.

Refrigerated Vapor Condensation

Refrigerated vapor condensation is a type of surface condenser used to remove VOC from gas streams where the surface is cooled by refrigeration to temperatures far below zero [2]. Refrigerated condensers can achieve high removal efficiencies and are used in applications where process streams contain highly volatile organics which require the low temperatures for condensation. A dehumidifier is required upstream of the refrigerated condenser to remove as much of the water vapor as possible to avoid icing.

Refrigerated vapor condensation is a well-established technology used only for highly volatile organic compounds.

Regenerated Hydrophobic Polymer Sorbent for VOC Control

In the mid-1990s, Purus developed the PADRE™ system that uses a hydrophobic polymer sorbent developed by Dow. The system consisted of dual fixed beds filled with sorbent that are alternately on-line (for collecting VOC) and off-line (for regeneration). The regeneration loop includes the off-line bed and an electric powered chiller. The condensate dripping off the chiller is collected in a waste product storage tank and recycled. Applications include air stripping and soil venting.

Supercritical Water Oxidation

When the temperature and pressure of water is brought above its critical point (where the pressure equals 22.1 MPa (3,191 psi) and temperature equals 374°C), water exhibits unique characteristics, many of which are particularly advantageous for environmental treatment.

Supercritical water oxidation is a promising method for industrial wastewater treatment [2]. Supercritical water oxidation is an emerging technology that takes advantage of these properties to effect waste treatment [1]. Supercritical water oxidation (also known as hydrothermal oxidation) is an innovative method for thermal conversion of biosolids, and report ongoing efforts to apply the process in industrial and wastewater treatment facilities [6]. It completely decomposes organic substances, produces a high-quality effluent, and is capable of producing Class A biosolids.

Contact: HydroProcessing LLC, Austin, TX, 512-339-9981, info@hydroprocessing.com.

Thermal Hydrolysis

Thermal hydrolysis is an innovative technology for stabilization of biosolids [6]. Parsons defines it as oxidation of sewage sludge under elevated temperature (approximately 160 °C) and pressure (approximately 700 kPa). Pathogens are destroyed and cell structures break down. Following hydrolysis, the sludge is fed to an anaerobic digester, resulting in higher volatile solids destruction (~65%) and increased biogas production, as compared to conventional anaerobic digestion. Pulp manufacturers in Europe use this technology.

Contact: RDP Technologies, Inc., Norristown, PA, 610-650-9900, pchristy@rdptech.com.

UV Disinfection – Monochromatic Lamp

UV disinfection applies powerful monochromatic ultraviolet light to kill the pathogens in all types of wastewater or recycled liquid streams. Industrial applications include treatment of metal removal fluids, sterilizing pharmaceutical and medical products, etc.

Triton Thalassic Technologies, Inc. (Triton) has developed a high-flow (300 gpm) disinfection system using monochromatic UV light to disinfect nearly opaque fluids such as metal removal fluids [10]. The UV light destroys pathogens, spores, fungi, and yeasts, often reducing concentrations by 5 orders of magnitude. The system was demonstrated at a Volvo plant in Sweden in 2000. Triton sold several systems to GM in 2001. More recently, Triton has pursued the pharmaceutical industry (e.g., contact lens), medical industry (blood sterilization), and the food and drink industry (e.g., fruit drinks, bottles).

UV Radiation – Broad-band Lamp

Ultraviolet (UV) light exhibits excellent germicidal properties at certain wavelengths. In addition, UV radiation can transform molecular structures making it useful in several industrial applications, such as pulp bleaching and in the curing of specialized coatings. However, this technology is well established with a number of reputable vendors of UV systems.

Jensen reports that UV is widely used in California for disinfecting drinking water instead of chlorine treatments [3]. They use medium-pressure lamps, which produce broadband UV light. The UV light causes mutations in the pathogen's DNA in sufficient degree to kill the pathogens.

Trojan Technologies and Aquionics have products using this technology.

Contact: Dr. James N. Jensen, University of Buffalo, Buffalo, NY, 716-645-2114 x2329, jjensen@eng.buffalo.edu .

Vacuum Pyrolysis

A Canadian firm, Groupe Pyrovac Inc., has developed a vacuum pyrolysis reactor process they call Pyrocycling™. The process was initially developed for the pulp and paper industry, and it produces phenolic-rich oil from softwood bark. Waste is thermally decomposed under reduced pressure. Byproducts are withdrawn from the reactor by a vacuum pump and recovered through condensation in the form of pyrolytic oils. The reactor was designed to operate at a capacity of 3.5 tons/hr of feedstock at 15% moisture content. The system may have many environmental applications.

Wet Air Oxidation

Wet-air oxidation is a liquid phase reaction in water using dissolved oxygen to oxidize wastewater contaminants [1]. The oxidation reactions, which occur at moderate temperatures and pressures, typically result in the conversion of organic contaminants to biodegradable short chain organic acids. Inorganic constituents such as sulfides and cyanides can also be oxidized, and the process can be used for high strength wastewater streams prior to final biological treatment. There are few commercial applications of the technology; there is little effort or interest in the technology; and it cannot be considered an emerging one [1].

B

REFERENCES

1. Emerging Environmental Technologies: An Analysis of New Treatment Technologies for the California Energy Commission; EPRI, Palo Alto, CA; California Energy Commission, Sacramento, CA: 2003, 1007411.

2. *Electrotechnologies for Industrial Waste Treatment,* EPRI, Palo Alto, CA: January 1996, CR-106144.

3. Private communication with James Jensen, University of Buffalo, September 5, 2007.

4. *Charnock Wellfield Site: Ex Situ Advanced Oxidation Processes (AOP), Granular Activated Carbon (GAC), and Synthetic Resin Adsorption Treatment of Drinking Water,* Draft MTBE Case Study, U.S. Environmental Protection Agency, July 2000.

5. *Dewatering treatment system and method*, Colin John Francis Philip Jones; John Lamont-Black; Stephanie Glendinning; Electrokinetic Limited; 2007; United States Patent No. 20070051682 (http://www.freepatentsonline.com/20070051682.html)

6. *The feasibility of electro-osmotic belt filter dewatering technology at pilot scale*, H.G. Snyman, P. Forssman, A. Kafaar and M. Smollen, Water Science and Technology, Vol. 41, No. 8, pp. 137–144, IWA Publishing 2000.

7. *Improved sludge dewatering by addition of electro-osmosis to belt filter press*, Hwang, S; Min, K S., Journal of Environmental Engineering and Science, Volume 2, Number 2, 1 March 2003, pp. 149-153(5).

8. *Emerging Technologies for Biosolids Management*, by Parsons Corporation, Fairfax, VA, for U.S. EPA Office of Wastewater Management, EPA 832-R-06-005, September 2006.

9. "Section 8.11 - Supercritical Water Oxidation," *Standard Handbook of Hazardous Waste Treatment and Disposal,* Frisch, Michael, Harry Freeman, editor, McGraw Hill, New York, 1998.

10. Private communication with Kevin Kurz, Triton Thalassic Technologies, Inc., September 6, 2007.

11. *Sewage Sludge Disintegration Using Ozone – A Method of Enhancing the Anaerobic Stabilization of Sewage Sludge*," by R. Vranitsky and J. Lahnsteiner, in Proceedings of the European Biosolids and Organics Residuals Workshop, Conference and Exhibition, 2002.

12. *Energy efficiency in drying*, Christopher G.J. Baker, Stewart Postharvest Review, Volume 1, Number 4, December 2005, pp. 1-11(11), Stewart Postharvest Solutions.

13. *Introduction to Hazardous Waste Incineration*, by Louis Theodore and Joseph P. Reynolds, Wiley-IEEE, 1987.

14. *Apparatus for the processing of solid mixed waste containing radioactive and hazardous materials*; Gotovchikov, V.T., Ivanov, A.V., and Filippov, E.A.; United States Patent No. 5,882,581, March 16, 1999.

15. *Safe Management of Wastes from Health-care Activities*, by Eric Giroult, Annette Prüss, and Philip Rushbrook, World Health Organization, 1999.

16. EPRI TechApplication No. 1, 1995.

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute (EPRI)

The Electric Power Research Institute (EPRI), with major locations in Palo Alto, California; Charlotte, North Carolina; and Knoxville, Tennessee, was established in 1973 as an independent, nonprofit center for public interest energy and environmental research. EPRI brings together members, participants, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. These solutions span nearly every area of electricity generation, delivery, and use, including health, safety, and environment. EPRI's members represent over 90% of the electricity generated in the United States. International participation represents nearly 15% of EPRI's total research, development, and demonstration program.

Together…Shaping the Future of Electricity

Printed on recycled paper in the United States of America

1016110

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com