

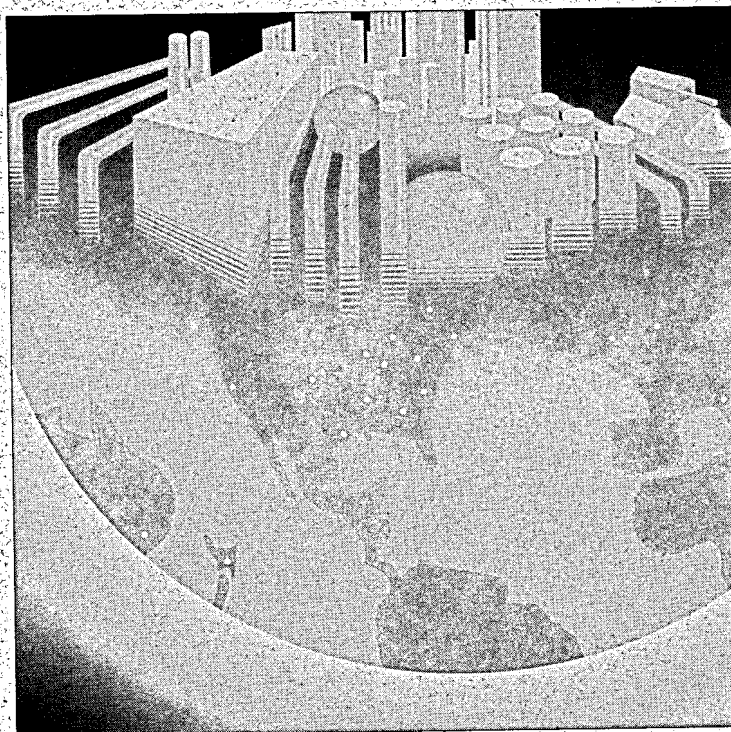
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UV Disinfection for Water and Wastewater Treatment

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A Summary of Existing and Emerging Ultraviolet Technologies for the
Disinfection of Drinking Water and Wastewater

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Prepared by
Black & Veatch
Kansas City, Missouri

and

The Electric Power Research Institute
Community Environmental Center
Washington University
St. Louis, Missouri

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4.0 Emerging Technologies

This chapter presents information on several non-conventional applications of UV radiation for disinfection of water and wastewater along with an introduction into related electrotechnologies.

4.1 Summary of Emerging Technologies

A summary of the technologies described in this section is presented in Table 5. This information shows the major application of each technology along with comparative advantages and disadvantages. Several of these technologies are already in use for chemical oxidation of micropollutants in contaminated groundwater. Others are adaptations of conventional water and wastewater disinfection technologies; for example, conventional UV combined with filtration or ozone combined with hydrogen peroxide. Still others are in the experimental phase. Many are adaptations of technologies used in food processing or developed from government research and their effectiveness in disinfecting water and wastewater treatment to achieve compliance with applicable regulations will require further study. For technologies still in the experimental phase, the full-scale attributes (capital and power costs) have not yet been defined.

Regulatory compliance will need to be addressed before these technologies are used for disinfection. In wastewater treatment, the degree of disinfection required is usually expressed as a maximum number of fecal or total coliforms measured in the treated effluent. This value is listed in the treatment plant's National Pollutant Discharge Elimination System (NPDES) permit. A commonly used limit is 200 fecal coliforms per 100 milliliters of treated wastewater on a monthly geometric average basis, with a maximum day limit of 400 coliforms per 100 milliliters. However, several states impose much stricter limits, depending on the receiving water quality. Still, these regulations are flexible enough to allow the use of new or novel disinfection systems with the approval of the local regulatory authority. This is in comparison to the disinfection of drinking water where credit for disinfection is handled differently.

Table 5 Summary of Emerging Technologies

Technology	Characteristics			Equipment Required					Possible Applications				Capital Costs			Electrical Use			Comments
	Direct Photolysis	Oxidation	Electroporation	Pulsed Electrical Source	Narrow Band Lamp	Broad Band Lamp	Ozone Generator	Chemical Feed	Disinfection	Organics Oxidation	Metals Oxidation	Metals Reduction	High	Moderate	Low	High	Moderate	Low	
High Intensity UV	●				●	●		●	●			/		●				●	Present Status
Broad-Band Pulsed Xenon	●			●					●										Special Requirements
Narrow-Band Excimer	●			●	●				●										Attributes
Pulsed Electric Field			●	●					●	●									Commercial development underway
Ozone/UV		●			●		●		●	●	●		●			●			Used in other industries
Ozone/H ₂ O ₂		●					●	●	●	●	●			●			●		Presently experimental model only
UV/H ₂ O ₂	●	●						●		●	●								Used for cold pasteurization
UV/TiO ₂	●	●			●			●		●	●								O ₃ disinfection in use
VUV	●	●			●					●	●								O ₃ disinfection in use
																		●	Mineralization Possible
																		●	Mineralization Possible
																			Mineralization Possible

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The Surface Water Treatment Rule (SWTR) specifies minimum disinfection requirements for drinking water as 4 logs inactivation or removal of viruses and 3 logs inactivation or removal of *Giardia lamblia* cysts. While the capability to achieve these levels of inactivation can be demonstrated using "challenge" testing with actual measurements of microorganism concentrations, the usual method is to use the EPA's "CT" criteria. The CT concept, in which the water is exposed to a disinfectant concentration (C) for a certain period of time (T), includes specified minimum values for chlorine, chloramine, chlorine dioxide, and ozone (UV has CT values for viruses only). These values are measured daily by monitoring the flow rate and the disinfectant concentration. For new or novel disinfection systems, the question arises as to how CT values can be measured or calculated. For this reason, regulatory review and approval will be a major factor in implementing a novel drinking water disinfection process.

4.2 High Dosage UV

There have been several modifications made to reactor design in which UV can be applied at extremely high dosages through either the use of high intensity lamps or other means. In some cases, the protozoa would be removed from the liquid and retained on a membrane filter. The filter would then be irradiated with UV to inactivate the organism. This provides an extended exposure time to the UV radiation and increases the dosage accordingly. Recent findings on inactivation of *Cryptosporidium* indicate that the combination of conventional, low-pressure UV lamps with retention of organisms on membrane filters was able to provide between 2 and 3 logs of inactivation at a dosage of 8,748 mW-sec/cm² (Campbell, et al, 1995).

4.3 Lamp Technology

While commercialized UV disinfection systems utilize either low-pressure or medium-pressure mercury lamps, research is being conducted into the use of other types of lamps for specialized applications. Much of this research is based on the findings from industrial applications of UV technology. For example, industries which produce or use inks, coatings, and adhesives utilize high-intensity UV lamps to cure their products on the production line as an alternative to conventional thermal drying. The use of radiative treatment for inactivating microbes and pests on fresh fruit and vegetables has been commercialized over the past few years and is experiencing wider application as an alternative to pesticide and fungicide application. While these

applications differ considerably from those used for water and wastewater treatment, they are used as the basis for research into UV technologies that may become applicable for disinfection.

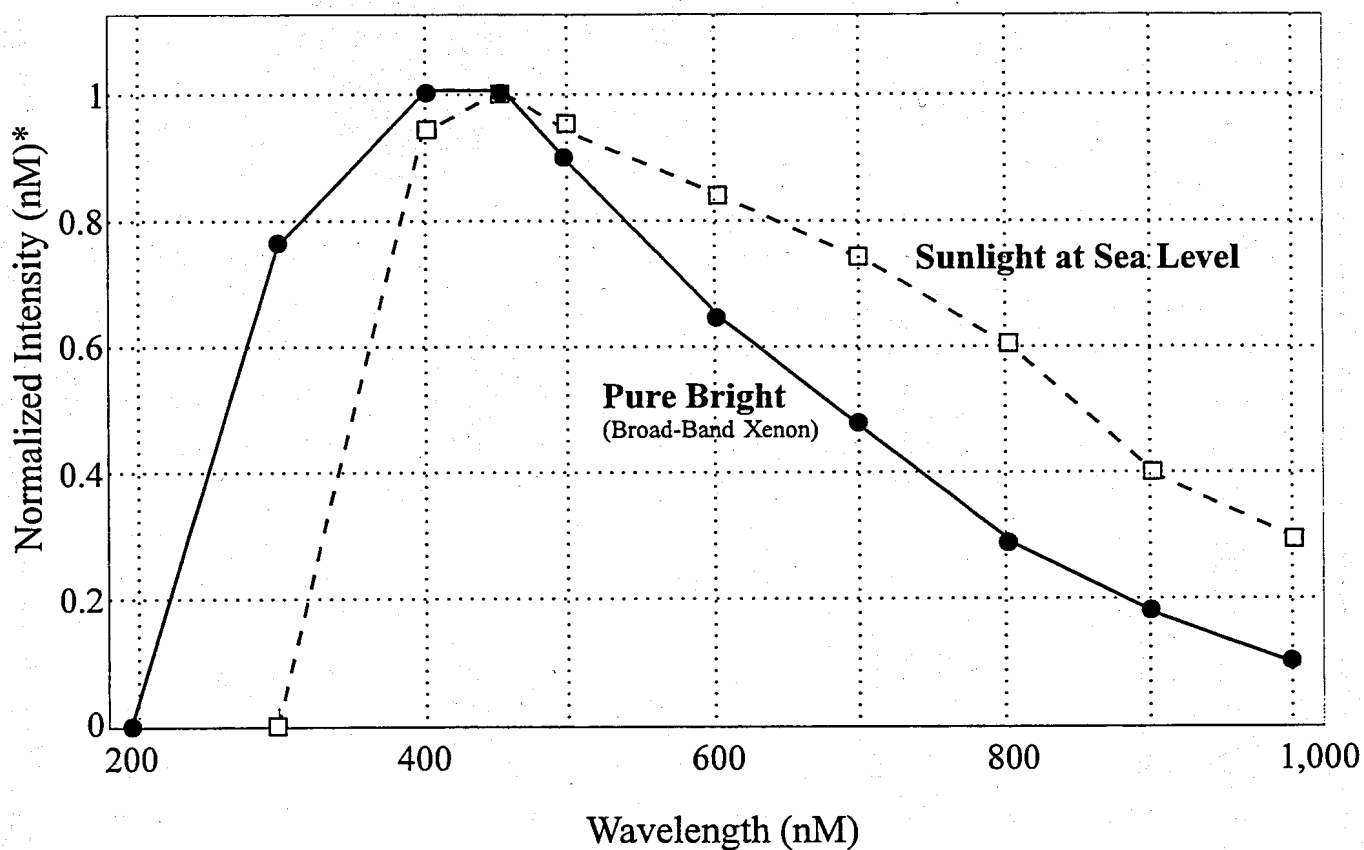
4.3.1 Broad-Band Pulsed Xenon

The use of pulsed energy source, broad-band xenon lamps is being investigated for two purposes: high-rate sterilization systems in food processing and in the disinfection of drinking water and wastewater. These lamps emit radiation at a wide array of wavelengths (Figure 12). While radiation of germicidal wavelengths constitutes only a small portion of the total emission, the high intensity of this system may find an application in water and wastewater treatment. One supplier to the food processing industry, PurePulse Technologies, Inc (formerly Foodco Corporation) of San Diego, California, is researching into the applicability of its food treatment system for drinking water disinfection.

In food processing, the normal exposure time to a medium-pressure UV system is on the order of seconds. The pulsed UV system, offered by PurePulse, works in only a fraction of a second and provides much higher microbial inactivation. This rapid exposure allows the use of a small, broad-band UV system on high-speed production lines to treat product before packaging. In the disinfection of drinking water, information from a single set of tests performed by the manufacturer on the efficiency of a laboratory-scale, broad-band pulsed xenon source indicates up to a 7-log removal of *Cryptosporidium* oocysts (Arrowood, 1995). In comparison, a conventional low-pressure or medium-pressure lamp is expected to have no discernable effect on *Cryptosporidium* oocysts. Research is being conducted with the Center for Disease Control to verify the effects of broad-band, pulsed xenon lamps for this application.

For a "pulsed" UV system, AC line current is converted to DC and stored in a capacitor as indicated on Figure 13. This energy is released through a high-speed switch as a "pulse" to produce radiation from a lamp or to generate intense electric fields. The pulsed-source concept is similar to that of a heart defibrillator. The defibrillator stores energy to be discharged over a short period at a high intensity across a patients chest . However, the defibrillator operates at a low voltage (1,000 volts) whereas a pulsed UV system would operate at a higher voltage.

The charge is stored up over fractions of a second and discharges within a few 100 microseconds. The lamp is fired when the switch closes, producing a plasma



* PureBright Approximately 20,000 times the intensity of sunlight at sea level.

Figure 12: Broad Band Lamp Emissions vs. Sunlight Emissions
(Courtesy of Pure Pulse)



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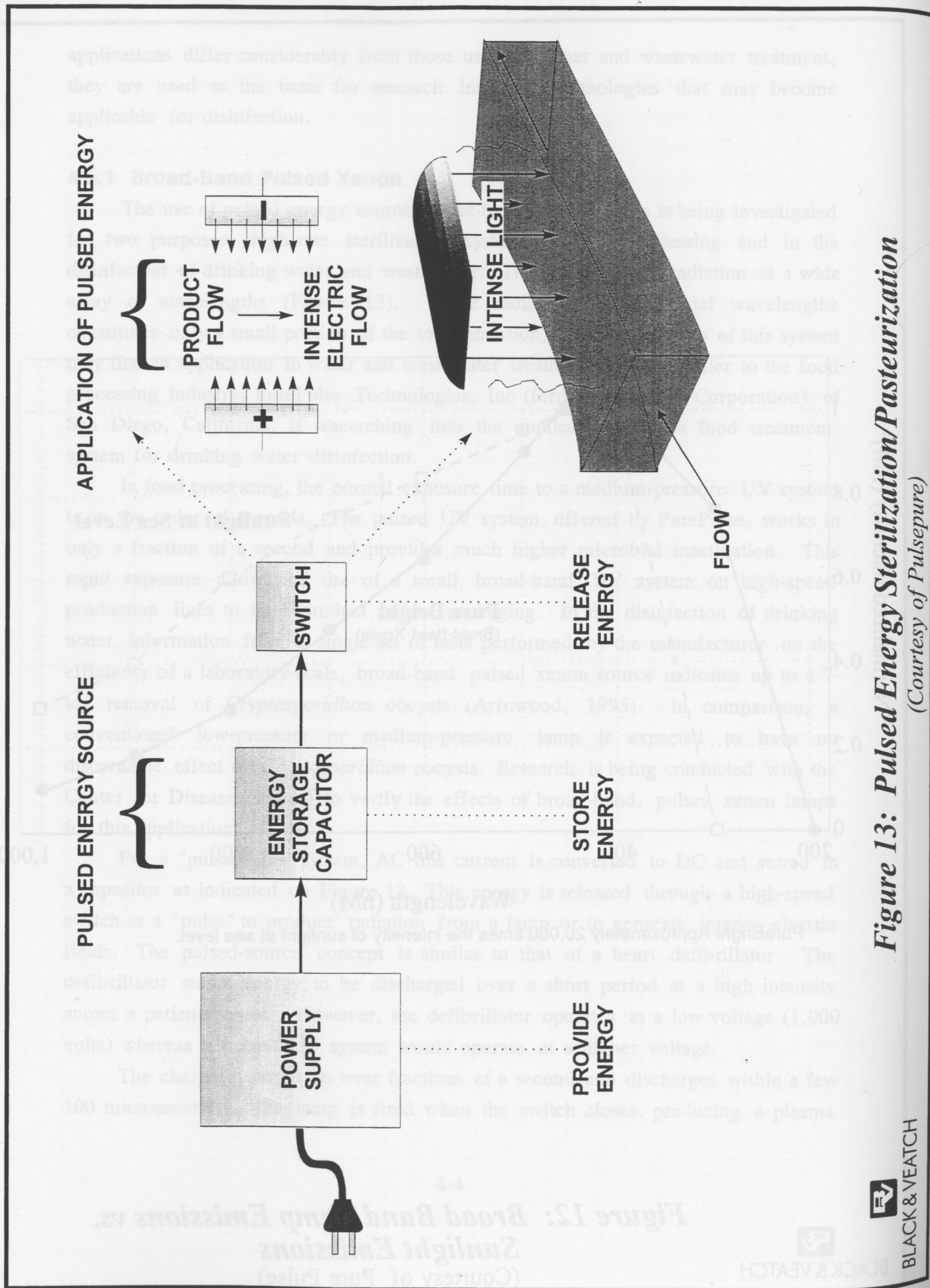


Figure 13: Pulsed Energy Sterilization/Pasteurization
(Courtesy of Pulsepure)

(ionized gas). The plasma expands until it reaches the wall of the lamp (a confined plasma). Electrical current carried by the plasma results in ohmic heating, raising the temperature of the plasma to approximately 10,000 Kelvin. At this temperature, the hot plasma emits an intense, broad-band spectrum at UV, visible, and infrared wavelengths.

In general terms, the lamp spectra produced by photon emission can be compared to sunlight. The pulsed lamp can produce radiation approximately 20,000 times as intense as sunlight at sea-level (Figure 12). It has been theorized that a synergistic relationship is present between the UV and visible wavelengths produced by this system (because of the high intensity), resulting in improved disinfection.

The application of this technology to drinking water disinfection will also require experimentation with reactor design. Preliminary projections by the system supplier indicate that a reactor would be similar to the enclosed chamber used for medium-pressure UV systems (Figure 10). A reactor of this design would treat up to 750,000 gpd using a single bulb with an irradiance of 100 mW-sec/cm² at the chamber wall. Similar to the medium-pressure units, a cleaning system would be provided to remove scale deposits. In addition, back-up systems would be necessary to provide disinfection during periods of maintenance. Currently, the lamps used for this application have a rated life of 1,000 to 2,000 hours.

The supplier expects capital costs for this type of system to be \$50,000. This would include the power supply, reactor, and controls but not redundant units. Operating costs will need to be determined but would include power, lamp replacement, and operations and maintenance labor.

4.3.2 Narrow-Band Excimer

While the pulsed xenon lamp produces a broad band of radiation, research is also being conducted into several types of lamps that produce a near-monochromatic emission. The lamps use a corona discharge to form excited dimers (excimers). The gases used for this purpose include xenon (Xe), xenon chloride (XeCl), krypton (Kr), and krypton chloride (KrCl). One lamp manufacturer encloses the gas in quartz, with an inner electrode (inside the inner sleeve) and a wire mesh outer electrode (outside the outer sleeve) as shown on Figure 14. The current flow in the discharge gap consists of a large number of microdischarges lasting only a few nanoseconds. During these short discharges, the electrons collide with the gas molecules, causing the molecules to collide in an excited state, forming dimers. The dimers are unstable and

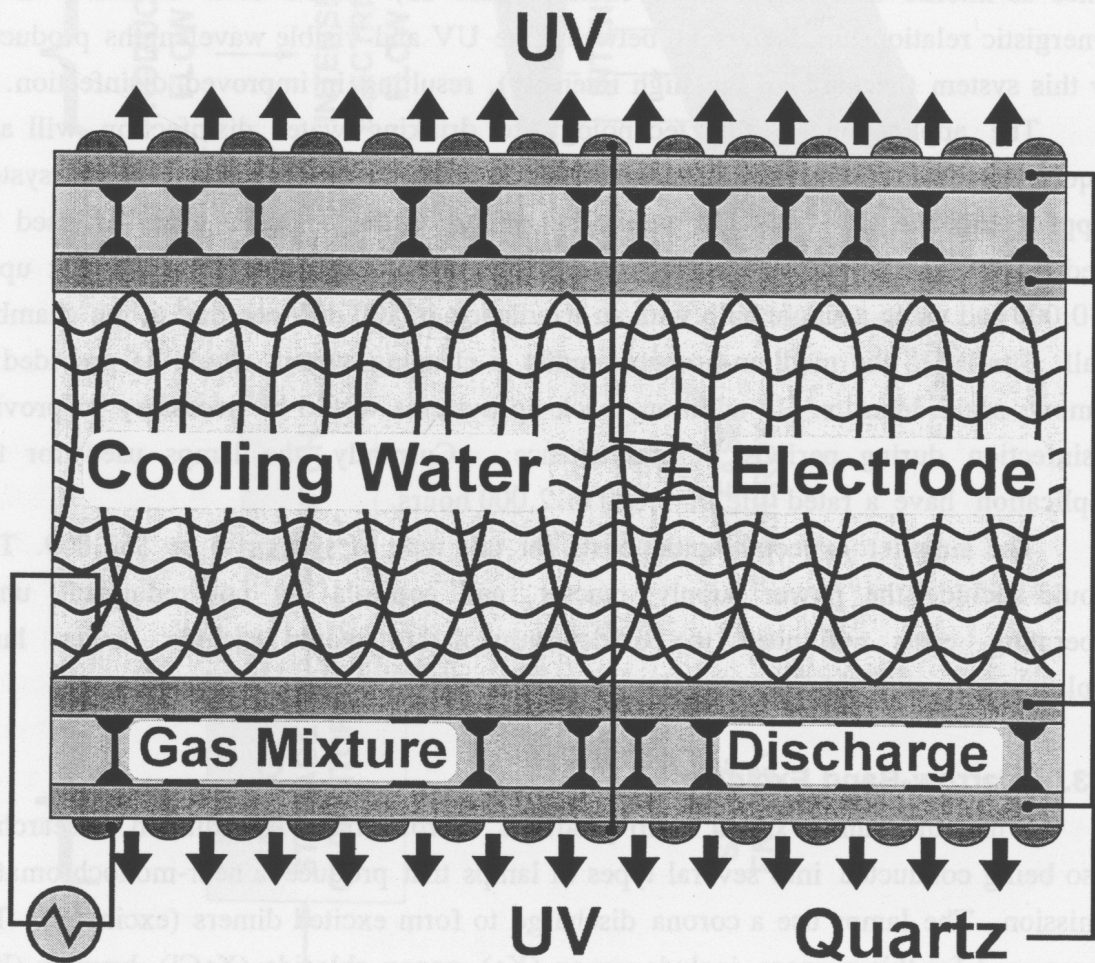


Figure 14: Excimer UV Lamp
(Adapted from Heraeus)

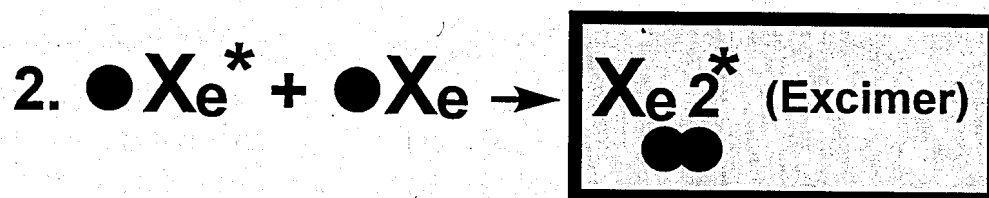
collapse into the normal state, releasing energy in the form of photons, as shown on Figure 15.

Research at the University of California-Davis (UCD) is directed at narrow-band, pulsed UV systems for water and wastewater disinfection. The initial research in this field was centered on the use of excimer lasers for removal of microbial pollutants and pesticides from agricultural irrigation waters. As a conservation measure, nursery irrigation water is recycled and filtered for reuse. However, after a number of cycles, the concentrations of microbes and pesticides increase to unacceptable levels and the water is discharged as waste. Usual practice is to filter the recycled water and chlorinate in some cases. The results from the excimer laser experiments are very promising (MacDonald, 1994). Similar to the microbial inactivation portion of this application, the high intensity excimer lamp is being examined for use in water disinfection.

The excimer lamp's output is quasi-monochromatic (almost all of the energy released is at one UV wavelength). There is a very small output in the infrared region. The emission wavelength is a function of the gas used in the lamp. Commercially available excimer lamps can be tuned to three wavelengths: 172, 222, and 308 nanometers. Figure 16 shows the gas mixtures used to emit at these wavelengths, along with others that are being developed for use in excimer lamps. The excimer lamp requires a high frequency, high voltage power source. The system operates at several hundred kilohertz. The power source can be modulated to control output from the lamp.

The main difference between these lamps and a laser is that the laser produces coherent, non-divergent radiation. The excimer lamps produce divergent (in many directions) and incoherent radiation. To produce a coherent emission, the laser uses mirrors to redirect the photons back into the gas to stimulate the release of more photons. A portion of this light is then bled off to form the laser output. The optics used for a laser add considerably to the cost of the system. By eliminating the laser optics, the excimer lamp system would be much less expensive.

Several items must still be examined to make this technology available for water and wastewater treatment. For instance, the lifetime of these lamps is approximately 1,000 hours. If fluoridated noble gases are used, fluorine may be produced in the dimerization process. Fluorine has been known to etch into the quartz, resulting in lamp failure. In addition, the cost for a small excimer lamp and power supply is approximately \$25,000. Depending on the amount of water that could be treated



1. Excitation Process
2. Excimer Formation
3. Excimer Decomposition
generating UV-Light

Figure 15: Cycle of Excimer Process
(Adapted from Heraeus)



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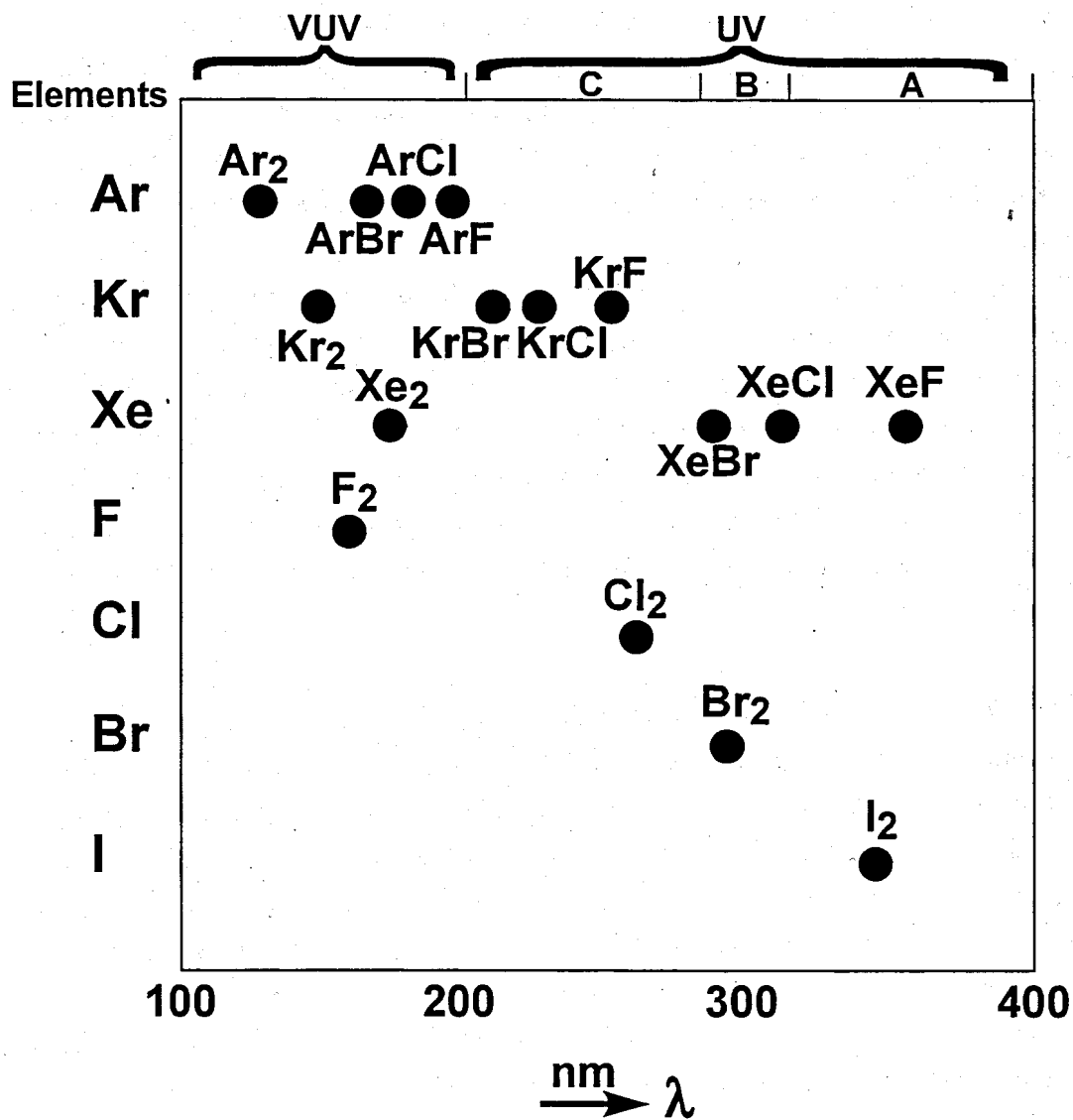


Figure 16: Excimer Emission Wavelengths
(Adapted from Heraeus)



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with one lamp, this cost may be prohibitive. It is expected that costs would decrease as the use of the lamps increases.

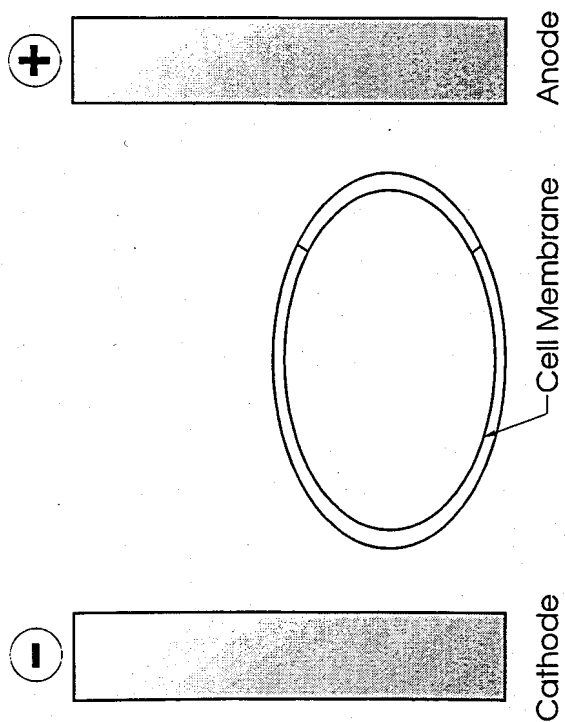
4.4 Pulsed Electric Fields

Research is being conducted into the application of pulsed electric fields for water disinfection. This process involves passing the liquid to be disinfected through a strong electric field. The electric field causes structural changes to occur in the cell, elongating the cell membrane as shown on Figure 17. With a sufficient electric field, localized sites in the cell membrane will be altered to a point where small pores are formed in the cell wall. This process is referred to as electroporation. The strength of the electric field required to reach pore formation depends on the characteristics of the cell (wall thickness, cell volume). Once the cell wall has sufficient pores formed that allow the chemical balance inside the cell to be disrupted beyond repair, the cell dies.

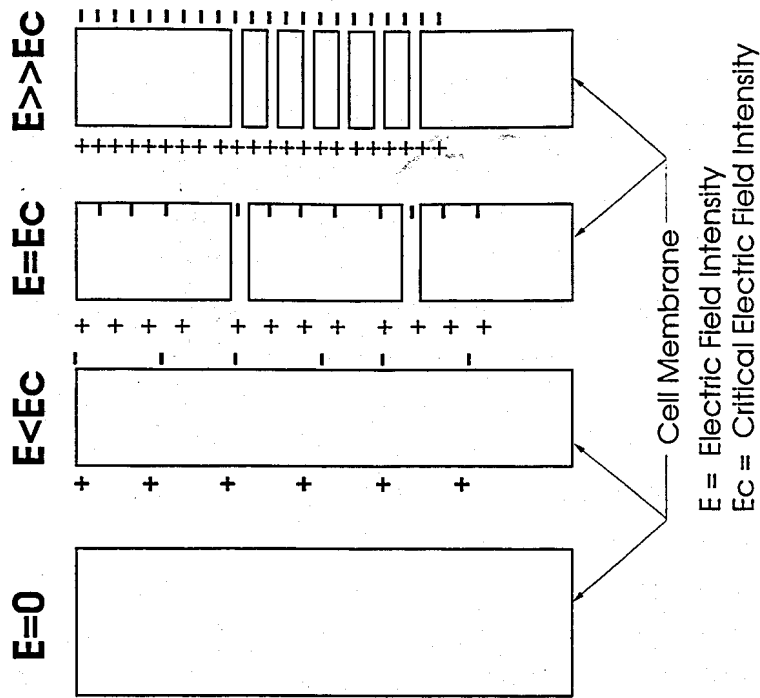
This process has been researched for use in the pasteurization of milk, juices, and other liquids. While it does not involve the use of irradiation, it uses a power source similar to those in the pulsed UV technologies. In its simplest form, the pulsed electric field would consist of a pulsed power source, high voltage electrodes, and a reactor as shown on Figure 18. The efficiency of this process depends on the intensity of the electric field required to achieve cell pore formation, the resulting capital cost of the equipment, and the amount of maintenance required for its long-term operation.

4.5 Advanced Oxidation Processes

Advanced oxidation processes (AOPs) involve the production of hydroxyl radicals ($\text{HO}^\bullet$) through the use of various combinations of UV radiation, hydrogen peroxide (H_2O_2), and ozone (O_3). Hydroxyl radicals are extremely powerful oxidants, having an oxidation potential of 2.80 volts. In comparison, the oxidation potential of ozone is 2.07 volts. Hydroxyl radicals can be used to oxidize pollutants in drinking water and wastewater. In some cases, they can be used to completely mineralize organic micropollutants to carbon dioxide and water. However, while hydroxyl radicals are excellent oxidants, their efficiency as disinfectants is less than that of ozone (Labatiuk, 1993). Therefore, AOPs are better suited for oxidizing organic pollutants in drinking water than for direct disinfection.



Simplified System



Effects on Cell Membrane

Figure 17: Pulsed Electric Field (PEF) Effect on Microbes



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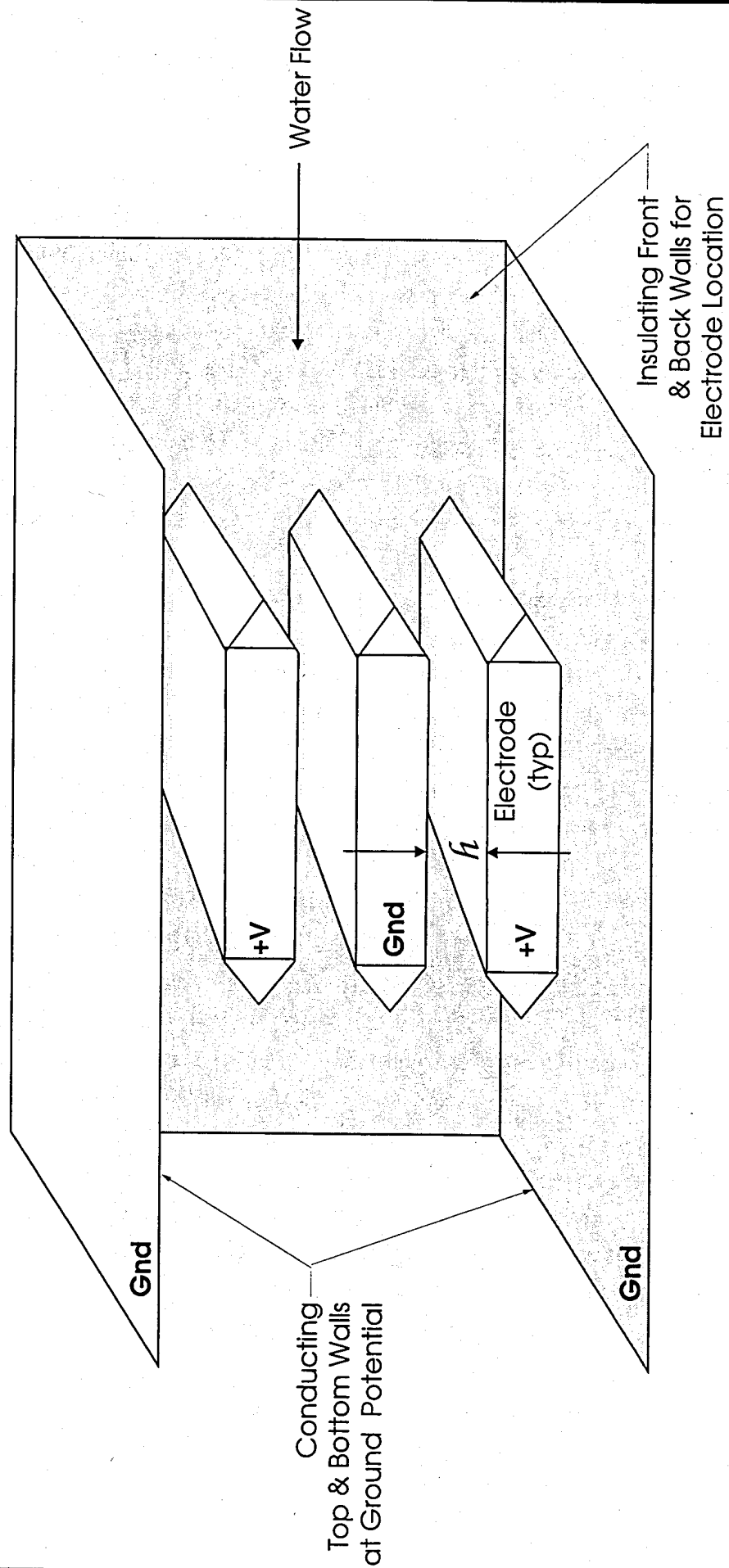


Figure 18: Potential PEF Contactor

Several systems using AOPS are presently in operation. The means of producing hydroxyl radicals vary among suppliers. The desired results of the oxidation process often drive the choice of AOP. For example, in large drinking water plants, ozone can first be added as a disinfectant in a multiple-baffled contactor. Hydrogen peroxide can be used in subsequent stages of the contactor (once disinfection has been achieved) to form hydroxyl radicals for oxidation of taste and odor compounds. This approach was incorporated into the design of the ozonation facilities at the East Bay Municipal Utilities District in Northern California. At a contaminated groundwater site in Kansas, hydrogen peroxide and UV were used to oxidize 1,4 dioxane and 1,2 dichloroethane. Several suppliers offer a UV/ozone system for organics oxidation.

In a related development, the direct photolysis of water using a xenon excimer lamp was shown to be an effective means to produce hydroxyl radicals (Braun, 1994). Water strongly absorbs radiation in the vacuum ultraviolet region (VUV) and dissociates, forming hydroxyl radicals in the process. This process is commonly referred to as VUV photolysis. The xenon lamp emits near monochromatic radiation at 172 nanometers, which, when absorbed by water, results in the following reaction.



This process offers the advantage of using fewer pieces of equipment and no chemicals when compared to the currently used combinations of UV, ozone, and hydrogen peroxide to produce hydroxyl radicals.

Along with AOPs mentioned above, there is also a great deal of research into the use irradiated titanium dioxide (TiO_2) for organics oxidation. In this process, a slurry or fixed bed of TiO_2 is irradiated with UV light, causing an electron "hole" to be formed on the surface of the particle (Legrini, et al., 1993). This electron-deficient hole can be used to directly oxidize micropollutants or to form hydroxyl radicals (which will in turn serve as an oxidant). In addition to the use of UV/ TiO_2 as an oxidation system, one supplier is actively promoting its use as a reducing agent for removal of dissolved copper and nickel. This approach takes advantage of "surplus" of electrons in the area opposite of the electron "hole".

Commercial use of the UV/ TiO_2 and the VUV photolysis processes is not as widespread as that of the other AOPs. Unlike ozone, which can be used for disinfection with later addition of H_2O_2 or UV for hydroxyl radical production, these processes do not have disinfection potential. Therefore, their use is restricted to oxidation and reduction processes.