ROLE OF LINEAR ACCELERATORS IN WATER TREATMENT

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ABSTRACT

Due to the aggressive industrial development in many countries, coupled with an increase in population in some of these countries, the need exists for more advanced and effective techniques for treating wastewater. Recent efforts searching for safe and practical alternatives have resulted in the consideration of the use of irradiation with high-energy electron beams. Such an electron beam can be produced by a linear accelerator (linac) of a few MeV's of beam energy. High-energy electron radiation purifies wastewater by converting toxic chemicals to benign products and destroying disease-causing microorganisms. Applications of linacs in cancer radiotherapy, medical sterilization, polymer treatment, and food processing, have provided the impetus for advancing linac design and manufacturing techniques. Current accelerator technology is capable of providing linacs that can produce high average power, enabling them to treat high-flow rate streams. Although the results are still at an initial stage, the possibility of use of high energy radiation in wastewater treatment is worth exploring. In this paper we will review the use of high energy radiation in decomposition and removal of water pollutants and include a brief overview of linacs. Examples of electron beam systems used for water treatment at some countries are presented.

INTRODUCTION

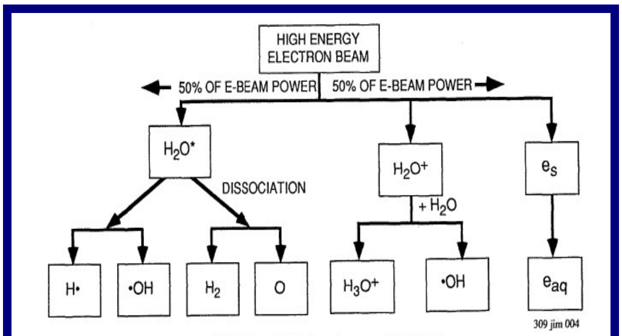
Industrial growth and population increases have resulted in the release of different pollutant compounds in the environment. In addition environmental regulations are becoming more restrictive on treatment of hazardous liquid effluents. Thus, the need exists to find new and increasingly more efficient pollution control methods. Radiation techniques are well established for sterilization of medical devices and polymer processing. Radiation processing of wastewaters is being investigated [1-5] as a potential water treatment technology due to its ability to penetrate the material and induce fundamental changes.

CONCEPT OF ELECTRON BEAM TREATMENT

Water is not normally reactive, but when it is subjected to ionizing radiation, it produces highly reactive species. The ionizing radiation can be produced by the use of a γ-radiation source (such as ^{60}C or ^{137}Cs) or the use of an accelerator that generates a high-energy electron beam. As the high-energy electrons impact flowing polluted water, the electrons slow down, lose energy, and react with the water to produce the three reactive species (hydrated electrons, hydroxyl radicals and H atoms) responsible for organic compound destruction. These short-lived radicals drive both oxidation and reduction reactions at the same time. High energy electron beam irradiation is the only process that is capable of forming both highly oxidizing and highly reducing reactive species in aqueous solutions at the same time and in relatively the same concentration. Furthermore, no other advanced oxidation process has the capability of generating as high an overall free radical yield per unit energy input as high energy electron beam treatment.

MECHANISM OF WATER RADIOLYSIS

When a high energy electron beam irradiates water, approximately 50% of the electron beam power goes into ionizing the water molecules forming H_2O^+. The other 50% of beam power results in excited water molecules, $H_2O^{\cdot}$. These primary reactions and subsequent secondary reactions products are shown in Fig. 1, [1].



G Values of Various Ions and Radicals

Product	H•	•OH	H_2	H_2O_2	H_3O^+	OH^-	e_{aq}
G Value	0.6	2.8	0.45	0.7	3.1	0.4	2.7

Fig. 1 Various ions and radicals formed by electron beam irradiation of water. The G value is defined as the number of species produced for every 100 eV of electron beam energy absorbed [1]

EXAMPLES OF ELECTRON BEAM IN WATER TREATMENTS

Removal of Organic and Petrochemical Pollutants in Brazil [2-4]

Researchers in Brazil have performed studies to predict how the electron beam (E-beam) treatment of industrial effluents can be considered a practical technology in removing organic contaminants in water treatment plants. One of their studies [4] compared the use of electron beam processing with activated carbon adsorption to clean up a real industrial effluent. The electron beam treatment was performed using an electron beam accelerator from Radiation Dynamics Inc. Table 1 summarizes some of their results in removal of six of the organic pollutants. It is shown from this table that an electron beam having a dose 50 kGy is sufficient to remove more than 99% of all of the six organic pollutants that were tested.

Table 1 Organic compounds removal by electron beam irradiation, [4]

Compound Percentage Removal	Electrom Beam Teratment Dose (kGy)					Activated Carbon (AC) Treatment
	5	10	20	30	50	
Benzene	93	97	99	99	>99	>99
Toluene	89	99	>99	>99	>99	>99
1,2 Dichlorethene	89	94	96	99	>99	>99
Chloroform	96	97	98	99	>99	>99
Bromoform	99	>99	>99	>99	>99	>99
Trichlorethylene	99	99	>99	>99	>99	>99
Methyl isobutyl ketone	76	94	97	>99	>99	>99

Brazilian researchers also compared the results of treating water polluted with three petrochemical pollutants with electron beam dose of 50 KGy with those processed by a convention treatment using activated carbon. A summary of the results of is listed in Table 2.

They concluded form the results summarized in Tables 1&2 that the E-beam process shows organic removal efficiency similar to that of the more conventional treatment using the activated carbon process if adequate irradiation dose was delivered to the organic pollutant.

Table 2 Degradation of organic compounds from petrochemical effluent using electron beam process and activated carbon, [4].

Petrochemical Pollutant (ppm)	Electron Beam Treatment Dose (KGy)		Activated Carbon (AC) Treatment
	0	50	
Benzene	11.00	0.04	0.03
Toluene	3.20	0.11	0.11
Xylene	10.30	0.15	0.15

Electron Beam Plant for Wastewater Treatment in South Korea [5]

In South Korea, an electron beam treatment pilot plant for treating 1,000 m^3/day of dyeing wastewater was constructed in Daegu and has been in operation since 1998. It utilizes an accelerator having the energy of 1MeV and producing beam power of 40 kW. The system is shown schematically in Fig. 2. For the uniform irradiation of water, nozzle type injector with the width of 1.5 m is used. The wastewater is injected under the E-beam irradiation area through the injector to obtain the adequate penetration depth. The speed of injection can be varied to achieve certain dose. This plant is combined with a biological treatment system. It demonstrated the reduction of chemical reagent consumption, and also the reduction in retention time with the increase in removal efficiencies of up to 30~40.

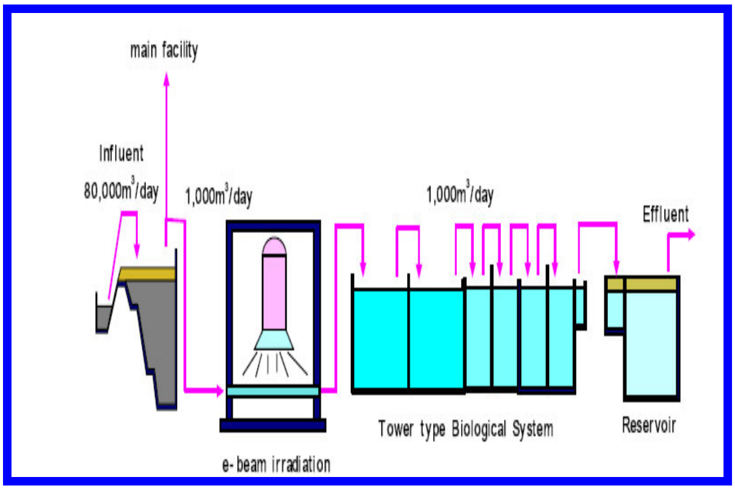


Fig. 2 Schematic of the pilot water treatment plant in Daegu, South Korea, [5]

Example of Research in the United Sates [6]

In the United States, one of the examples demonstrating the effectiveness of the use of electron beam in treating groundwater contaminated with volatile organic compound (VOC) was the research done by the High Voltage Environmental Applications, Inc. (HVEA) and demonstrated in 1994, [6]. This research aiming at developing E-beam technology was funded by the Superfund Innovative Technology Evaluation (SITE) program established by the U.S. Environmental Protection Agency. Fig. 3 shows a schematic of the HVEA E-beam treatment system. The E-beam was contained in an 8-by 48-foot trailer (2.44m by 14.64m). The E-beam system treated about 70,000 gallons of groundwater contaminated with VOCs at a maximum flow rate of 50 gallons per minute (gpm). The E-beam system includes the following components: a strainer basket, an influent pump, the E-beam unit, a cooling air processor, a blower, and a control console (not shown in Figure 2). These components are situated in three separate rooms: the pump room, process room, and control room. E-beam power rated up to 25 kW. For the run with the best overall performance, the removal efficiencies (RE) observed for trichloroethylene (TCE) and tetrachloroethene (PCE) were 98% and 99%, respectively.

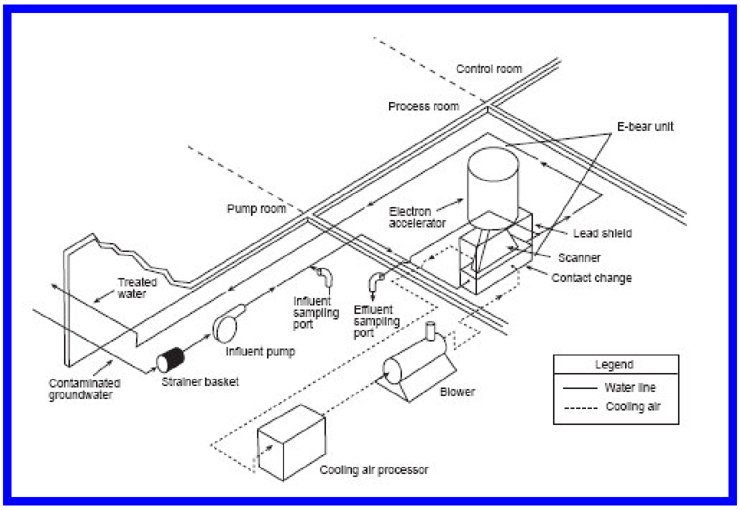


Fig. 3 Schematic of the HVEA E-beam treatment system, [6]

ELECTRON BEAM GENERATION

The high-energy electrons are generated using a linear accelerator (linac). Two types of accelerating structures have been developed for the acceleration of electrons:

(i) Traveling-wave structure;
(ii) Standing-wave structure.

In the traveling-wave structure the microwaves enter the linac on the gun side and propagate towards its high energy end, where they either are absorbed without any reflection or exit the linac to be absorbed in a resistive load or to be fed back to the input end of the linac as shown in Fig. 4, below.

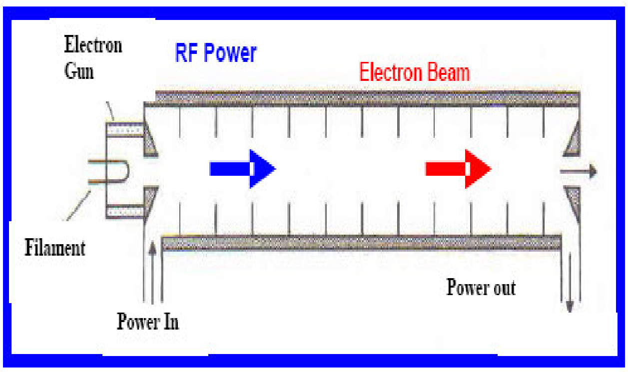


Fig. 4. Schematic of a traveling-wave linac, [7]

In the standing-wave structure each end of the linac is terminated with a conducting surface to reflect the microwave power, resulting in a buildup of standing waves in the accelerator structure. The establishment of a standing-wave pattern is illustrated in Fig. 5.

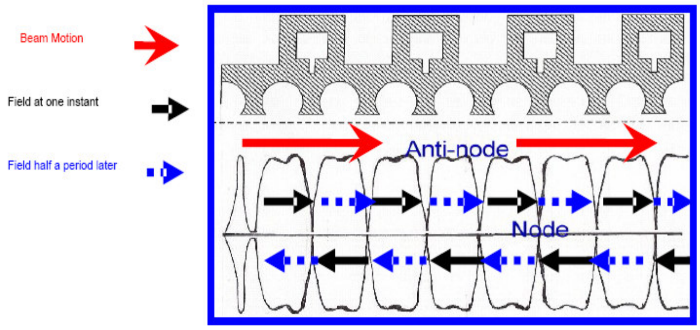


Fig.5. A standing wave pattern in a linac

In side-coupled standing-wave linacs, two sets of cavities exist. The on-axis cavities are the accelerating cavities, where the axial RF electric filed exerts the accelerating forces on the electron beam. In addition, another set of cavities exist to provide the path for the flow of the microwave and provide the resonant coupling between the on-axis accelerating cavities. A cut-away view of a 6 MV standing wave side-coupled linac [8] is shown in Fig.6.

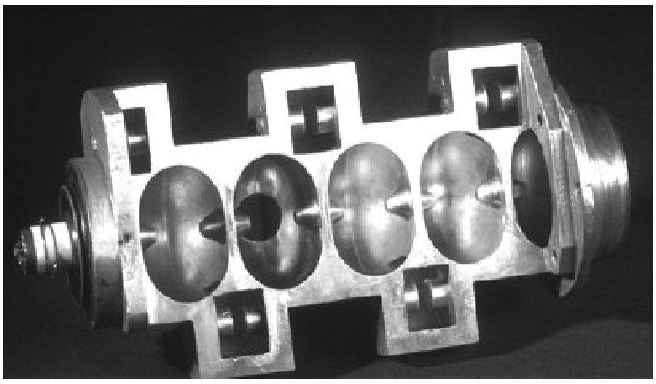


Fig. 6. Cutaway view of a standing wave accelerating linac. The cavities are clearly visible: the accelerating cavities are on the central axis; the coupling cavities are off-side, [8]

The source of electrons in a linac is normally a thermionic gun similar to the electron gun depicted in Fig. 7. The cathode is normally made of porous tungsten impregnated with barium oxide, aluminum oxide, and calcium oxide to enhance the thermionic emission by reducing the work function of cathode.

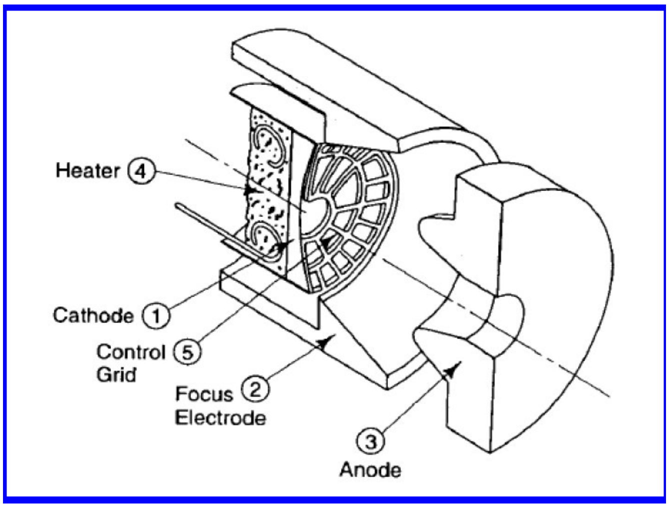


Fig. 7. Schematic cutaway view of a triode thermionic electron gun, [8]

The high-power RF fields used for electron acceleration are produced by microwave amplifiers such as Klystrons or by microwave oscillators such as Magnetrons. These high-power sources are pulsed by high voltage modulators. A Circulator is inserted between the linac and the microwave source to prevent the power reflected from the linac from returning to the RF source. Auxiliary systems provide a high vacuum inside the accelerator structure and cooling temperature control of its internal conducting surfaces.

CONCLUSION

Electron accelerator is a mature technology and represents a viable solution to the problem of waste water treatment. Several countries have already taken the initiative of implementing electron beam in the irradiation of wastewater. It is expected that the spread of use of this technology will provide the impetus for the accelerator industry to produce linacs specially designed for this application. It is hoped that the increase in number of units produced would help the cost of such technology to decline to a level that makes it affordable to many countries.

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