Chapter 22

FUTURE DEVELOPMENTS IN RADIATION PROCESSING

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1. INTRODUCTION

Radiation chemistry is a branch of physical chemistry, like photochemistry, plasma chemistry, ultrasonic chemistry, *etc*. Shortwave electromagnetic radiation (gamma radiation or X-rays) and high-penetration corpuscular (electrons) radiation transfer energy on a continuous, even into high density matter. Ionizing radiation, in the form of X-rays, gamma radiation, and electrons, produces abundant secondary electrons. The collision of a photon with a molecule usually causes an electron to be ejected *via* the Compton effect. Thus, nearly all of the physical and chemical changes in the system are produced by energetic electrons and not by the initiating photons. The kinetics of reactions induced by photons are similar to those obtained if electrons are used as the primary radiation. Therefore, there is no major difference in the effects caused by these different forms of radiation. Depending on the energy transferred, molecules can undergo ionization, excitation, or thermal transfer. Interaction with matter can be divided by time scale into the following stages: initial physical processes, pre-chemical reactions, chemical reactions, and, finally, radical diffusion. The time scale for the physical stage is on the order of 10^{-16} s. Electron excitation occurs in the range shorter than $\sim 10^{-10}$ s and vibrational excitation in the range 10^{-14} to 10^{-11} s. Molecular dissociation takes place in the range 10^{-14} to 10^{-6} s, centered at 10^{-10} s. Reactions governed by diffusion take place in the range $\sim 10^{-10}$ to $\sim 10^{-6}$ s. In liquid systems, it takes an ion pair about 10^{-5} s to separate and become free ions. Following these primary events, the ions, secondary electrons, and excited molecules undergo further transformations, exchanging charges and energy and reacting with the surrounding molecules, thereby producing free radicals and other reactive species which finally evolve into new stable products.

The physical, chemical, and biological effects of ionizing radiation on matter form the basis for many practical applications [1]. The number of such applications is growing, and the sources for gamma radiation and X-rays are now being operated in diverse environments. They play an important role in the economic development of many countries.

2. RADIATION SOURCES AND PROCESSING PLANTS

Three main sources of radiation are used in radiation processing. These are electron accelerators, gamma sources, and X-ray units based on the e^-/X conversion process. Accelerators are available for supplying electron beams (EB) in the energy range up to 10 MeV, and sources of the radionuclides cobalt-60 and cesium-137 emit gamma rays at 1.17/1.33 and 0.662 MeV, respectively. The introduction of new powerful X-ray (bremsstrahlung) radiation sources opens up new, until now largely unexplored, fields. Electron beams are corpuscular radiation and have limited penetration. The entire energy of electrons is deposited into relatively thin layers in materials. In the case of X-rays and gamma rays, ionizing radiation is produced by photons, which have no mass, and are thus able to penetrate deeper into materials. Cobalt-60 emitted gamma rays penetrate ~300 mm of unit density material on an equal entrance-equal exit basis. By contrast, the highest electron energy used in commercial applications, 10 MeV, only penetrates ~38 mm. The dose rates for gamma and X-rays are four to five orders of magnitude lower compared to EB. Therefore, the product throughput for gamma and X-rays is significantly lower than that of electron beams: electron beams are capable of delivering 100 kGy/s, whereas the typical dose rate for gamma rays is 2.8×10^{-3} kGy/s or ~10 kGy/h. X-rays are one order of magnitude higher in dose rate than gamma rays at 2.7×10^{-2} kGy/s or ~100 kGy/h. The radiation dose delivered over the same time period by an electron accelerator of just 15 kW power is approximately equal to that delivered by a 1 MCi cobalt source. X-ray target conversion efficiencies vary with the atomic number of the metal used; they are typically in the range of 8 to 12%. In practice, this means that in order to X-ray process products with the same manufacturing rate as a 10 MeV, 50 kW electron beam, the EB source for X-ray generation will have 417 kW of power, but will provide significantly greater depth of penetration.

2.1. GAMMA IRRADIATORS

The radiation processing industry gained significant impetus with the advent of nuclear reactors, which have the capability of producing radioisotopes such as cobalt-60. These gamma-ray emitters became popular radiation sources for research, medical and industrial applications. Many commercial sized gamma--ray irradiators have been built, 200 of which are estimated to be in current operation. Recently, the use of electron accelerators as radiation source equipped with an X-ray converter is increasing. However, gamma sources are difficult to replace, especially for use with non-uniform, high density products. Currently, cobalt-60 is almost solely used as an industrial gamma radiation source, mainly because it is easy to produce and it is not soluble in water. Based on the total cumulative sale of cobalt-60 by all suppliers, it is estimated that the installed capacity of cobalt-60 is increasing at the rate of about 6% per year. It is interesting to note that the worldwide use of disposable medical devices is also growing at approximately the same rate (5-6%), which seems to be driving the growth of cobalt-60 sales. The most suitable gamma radiation sources for radiation processing are cobalt-60 and cesium-137 because of the relatively high energy of their gamma rays and fairly long half-lives (30.1 years for cesium-137 and 5.27 years for cobalt-60). However, the use of cesium-137 has been limited to small, self-contained dry storage irradiators, used primarily for the irradiation of blood and for insect sterilization. In the United States, the use of cesium-137 has come under more stringent regulatory control with the National Academies of Sciences, Engineering, and Medicine recommending that it should be removed from the market and replaced by alternatives, such as small X-ray devices. Currently, all industrial gamma-ray radiation processing facilities employ cobalt-60 as the gamma radiation source [2].

The high capital costs and increasing regulatory demands have limited the growth of industrial gamma-ray processing facilities. However, the Nordion GammaFIT™ market-entry irradiator offers a gamma source at minimal capital investment. It is designed for optimal processing and flexibility to support future growth. Customers

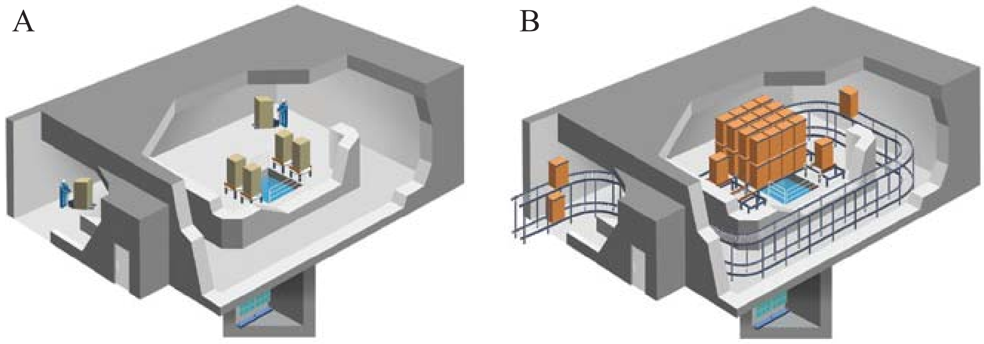

Fig.1. R&D small-scale irradiator (A) upgraded to a four-pass automated tote unit (B) [3].

can choose to start at the irradiator configuration which best suits their current business needs, with the option to change and upgrade as their business needs grow. Higher volumes or changes in product mix warrant an upgrade to a configuration with higher capacity. A scheme of a research and development small unit which can be upgraded to a four-pass automated tote irradiator is presented in Fig.1. The modular design minimizes irradiator downtime during an upgrade [3].

2.2. ELECTRON ACCELERATORS AND e^-/X UNITS

Electron beam accelerators have emerged as the preferred radiation source for industrial processing since they offer advantages over isotope radiation sources, such as (i) increased public acceptance with no storage, transport or disposal of radioactive material issues; (ii) the ability to configure a manufacturing process for in-line processing; and (iii) higher dose rates resulting in much higher throughputs. During the 1980s and 1990s, accelerator manufacturers dramatically increased the beam power available for high energy electron accelerators. Some of this effort helped in meeting the demands of the sterilization industry. In this timeframe, the perception that bigger, higher power, higher energy equipment was better prevailed. The operating and capital costs of accelerators did not increase with power demand and energy output as much as the throughput increased. High power provided low unit cost for radiation treatment. In the late 1980s and early 1990s, advances in electron beam technology produced new higher energy, higher power EB accelerators suitable for use in the sterilization market on an industrial scale. The main challenge for EB was the limited penetration of electrons in irradiated materials, which

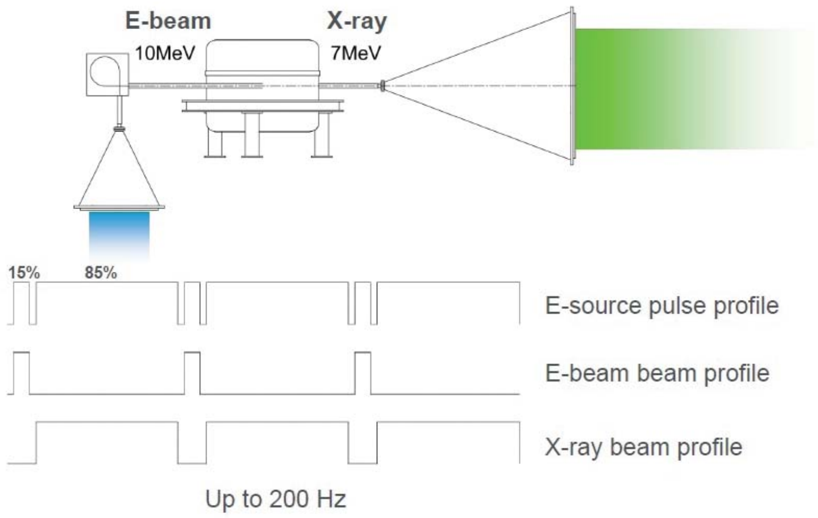

Fig.2. IBA system for X-ray or electron beam irradiation [4].

hampered the use of this technology for treatment of high density products and whole pallets. A solution has been high-powered IBA Rhodotrons™ with e^-/X converters. The relatively low X-ray conversion efficiency is overcome by increased beam power. Such a solution [4] is an IBA system for X-ray or electron beam irradiation, as shown in Fig.2.

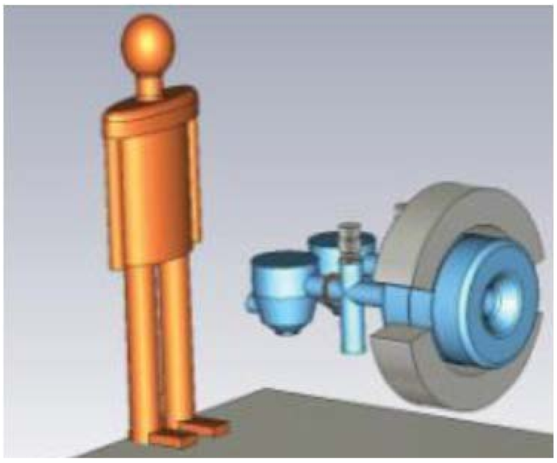

Fig.3. The new compact TT50 Rhodotron™ [4].

Another development from IBA is a compact TT50 Rhodotron™, as shown in Fig.3. The design target is a 80 cm cavity diameter unit [4] with the beam energy of 10 MeV and power of 10 kW. With its 20% energy efficiency, this unit will be a good tool for small- to medium-sized service providers and for research and development institutions.

3. MATERIALS PROCESSING

3.1. POLYMERS

Radiation processing has been used for nearly 60 years in industry for polymer modification [5]. The irradiation of polymeric materials with ionizing radiation (gamma rays, X-rays, accelerated electrons, ion beams) leads to the formation of very reactive intermediates, free radicals, ions and excited states. These intermediates can follow several reaction paths that result in disproportion, hydrogen abstraction, arrangements and/or the formation of new bonds. The extent of these transformations depends on the structure of the polymer and the conditions of treatment before, during and after irradiation. Thorough control of all of these factors facilitates the modification of polymers by radiation processing. The modification of polymers covers radiation crosslinking, radiation-induced polymerization (graft polymerization and curing) and the degradation of polymers. The success of radiation processing of polymers can be attributed to two reasons: (i) the ease of processing various shapes and sizes and (ii) many polymers undergo a value-added crosslinking reaction upon exposure to radiation. Some naturally occurring polymers have been difficult to process and degrade when exposed to radiation. Recently, some natural polymers are being looked at again with renewed interest because of their unique characteristics such as their inherent biocompatibility, biodegradability and availability. Many processes of the radiation treatment of natural polymers, though known for a long time, have not yet been commercialized, either because of the high cost of irradiation (high dose) or because of the reluctance on part of an industry to adapt to radiation technology. It is important to consider combining the beneficial effects of conventional technology along with radiation technology to overcome such issues. For synthetic polymers and natural rubber, there are well established irradiation processes. Naturally occurring polysaccharides have a wide range of uses in agriculture, medicine, cosmetics, food industry, and wastewater treatment. Some products based on radiation processed cellulose derivatives or chitosan have been developed and introduced to the market. Chitin is, next to cellulose, the second most abundant polysaccharide on earth. It is present in crustacean shells, insect exoskeletons, and fungal cell walls. Chitosan, (1-4)-2-amino-2-deoxy-β-D-glucan, is the deacetylated derivative of chitin. Commercially available chitosan is characterized by high molecular weight and low solubility in most solvents which limits its use. The solubility of chitosan can be increased by lowering the molecular weight. Water soluble chitosan can be prepared by oxidative degradation with H_2O_2 at a concentration higher than 1 mol/L. Low molecular weight chitosan can be prepared by chemical, radiation, or enzymatic degradation of the high molecular weight polymer. Radiation is one of the tools for the modification of polysaccharides. To decrease the molecular weight, a combination of chemical and radiation methods can also be used [6]. Chitosan oligomers have been obtained through irradiation of chitosan dissolved in acetic acid. Treating plants with oligochitosan increases their disease resistance and also stimulates their growth. Degraded polysaccharides such as alginate, chitosan, or carrageenan can increase tea, carrot, or cabbage productivity by 15 to 40%. Chitosan irradiated within the range of 70 to 150 kGy strongly affects the growth of plants as wheat and rice and reduces damage caused by vanadium. Radiation-degraded alginate in concentrations 20 to 50 ppm promotes the growth of rice seedlings, in concentrations at 100 ppm causes an increase of peanut shoots by approximately 60% compared to a control. Further progress in natural polymer processing is foreseen. One breakthrough factor could be the use of X-rays [7].

3.2. NANOTECHNOLOGY

Nanotechnology is a fast growing area in science and engineering. Radiation is used as a tool in this area. For many years, atoms and ions have been arranged using ion or electron beams. Radiation chemists in material processing follow a similar approach as do chemists in general, namely, that is treatment in the bulk. However, trends of more precise treatment technology have been followed as well, such as the use of surface curing, the development of ion track membranes and of controlled release drug-delivery systems. The ability to fabricate structures with nanometric precision is of fundamental importance to any exploitation of nanotechnology [8].

3.3. OTHER MATERIALS

Radiation processing can include gem stone colorization, the development of high temperature resistant fibers (SiC), and semiconductor modification [9].

4. STERILIZATION

Commercial radiation sterilization has been used for more than 50 years. Over the decades, there has been a substantial growth in the market for disposable medical products. With this, there has been significant growth in the use of ionizing radiation as a method for sterilization [10]. At present, 40 to 50% of all disposable medical products manufactured in North America are sterilized by radiation. Worldwide, there are now some 160 commercial cobalt-60 irradiators being used for radiation sterilization, operating in 47 countries and containing approximately 240 to 260 million Ci ($8.9\text{-}9.6 \times 10^{18}$ Bq) of gamma--emitting cobalt-60. Included in this calculation are service-type facilities operated in research and development centers. Because of the ability to down-scale cobalt-60 units, there are many research and development pilot-scale, small facilities as well, that are almost equal in number (~150). When other uses are taken into account, there are a total of over 300 gamma irradiators being operated for a variety of purposes in 55 different countries. Syringes, surgical gloves, gowns, masks, band-aids, dressings, medical tetra packs, bottle teats for premature babies, artificial joints, food packaging, raw materials for pharmaceuticals and cosmetics, and even wine corks are being gamma sterilized. An increasing number of electron beam accelerators are also being used, but for only a minority of radiation sterilized products.

5. FOOD IRRADIATION

A joint FAO/IAEA/WHO (Food and Agriculture Organization/International Atomic Energy Agency/World Health Organization) Expert Committee approved the use of radiation treatment of foods up to 10 kGy dose in 1980. After 1980, new regulations permitted the irradiation of foods which were not previously approved for this process in the United States. Experts agreed that radiation does not cause any toxicological changes or activation of irradiated food products. Therefore, toxicological tests for food treated by this method are not needed. Gamma rays or X-rays up to 7.5 MeV and electrons up to 10 MeV energy can be used for this purpose. The approvals of the irradiation treatment of packaged fresh or frozen uncooked poultry in 1990 and for the treatment of fruits, vegetables, and grains in 1986 are some of the examples of these new regulations. Today, more than 40 countries have permitted the use of irradiation for over 60 food products. The use of irradiation is becoming a common treatment for sterilizing packages in the aseptic processing of foods and pharmaceuticals. Spices represent the largest volume of irradiated food products. In 1988, the great International Conference on the Acceptance, Control of and Trade in Irradiated Foods, jointly sponsored by FAO, IAEA, WHO and ICT-UNCTAD/GATT (International Trade Centre-United Nations Conference on Trade and Development/General Agreement on Tariffs and Trade) was held in Geneva. The Document on Food Irradiation, adopted by consensus by government designated experts from 57 countries who attended the Conference, includes an important statement promoting the worldwide action on the development of detection methods for irradiated foods: "Governments should encourage research into methods of detection of irradiated foods so that administrative control of irradiated food once it leaves the (irradiation) facility can be supplemented by an additional means of enforcement, thus facilitating international trade and reinforcing consumer confidence in the overall control system" [11].

5.1. SPICES AND HERBS

Despite the great advances observed in modern synthesis-based pharmacy, medicinal plants still play an important role in contributing to health care. There has been a growing interest in alternative therapies in recent years, especially those derived from plants. The WHO estimates that about 65 to 80% of the world's population living in developing countries depends essentially on medicinal plants (herbs) for use in primary health care. Spices and herbs are often contaminated with high levels of bacteria, molds and yeasts. Most often the microorganisms, which are present on the surface of the plant, are a mixture of epiphytic microflora, growing on specific varieties of plants, and the microflora originating from the plant environment, namely soil, water and air. Pathogenic microorganisms may grow on some herbs and spice plants, and quite often they grow not only on the surface, but inside of the plant's tissue as well. If untreated, the herbs and spices will rapidly spoil the products which are supposed to enhance health. When contaminated with pathogenic bacteria, they can also result in serious food borne illnesses. Spices are usually decontaminated by irradiation or by fumigation with ethylene oxide gas (EtO). Some spices can be also steam treated. There is an extensive body of research available on the irradiation of spices, herbs and vegetable seasonings. Most products have been studied with at least preliminary if not extensive research, and the effects of irradiation on microbial contamination and sensory properties have been quantified. Since irradiation is a clearly preferable sanitation method, its use has been allowed by the Codex Alimentarius and by most countries worldwide [12]. While the use of EtO is allowed in North America, its use is not allowed in many European countries since EtO is a carcinogen when inhaled and it leaves harmful chemical residues on the spice. Typical pathogenic microorganisms present in herbs are *Staphylococcus aureus*, *Salmonella*, *Pseudomonas aerginosa, Clastridium perfringens* and *Candia albicans*. Opportunistic microorganisms are present as well; these are nonpathogenic microorganisms which, under specific conditions, may cause infection. These are the *Staphylococcus* type, *Enterococcus* and other rods from the *Enterobacteriaceae* family and *Pseudomonas* type, other nonfermentous rods, aerobic rods *Bacillus* type, most of the anaerobic rods of the *Clostridium* type, fungi imperfecti of the *Candida* and *Rhodotorula* type, and mold fungi, mostly *Mucor*, *Rhizopus* and *Aspergillus* types. There are different reasons as to why human organisms are infected by a nonpathogenic microorganism. These are metabolic aberrations (diabetes, renal insufficiency *etc*., long-lasting antibiotic therapy, radiotherapy, *etc*.). Especially sensitive to such a type of infections are children and elderly people. The other actions of microorganisms which are present in herbs may affect the quality of the final product. A chemical compound being a component of the drug may be destructed or its composition changed. Enzymes produced by microorganisms may react with other components of the drug to produce toxins or compounds having other pharmaceutical effects. The requirements regarding the microbiological purity for herbs were established by the WHO.

High contamination of herbs due to the presence of endospores of *Bacillus* and *Clostridium* and spores which are very resistant to the chemical and physical methods of decontamination, pose significant difficulties in the production of phyto-preparations. The use of physical or chemical methods, which reduce microbiological contamination to the desired level, quite often leads to the reduction of the content of the biologically active components. The sensory properties of most spices are well maintained between 7.5 and 15 kGy.

Research clearly indicates that irradiation maintains the sensory properties of spices, herbs and vegetable seasonings better than EtO treatment. Generally, the sensory properties of spices are more resistant to irradiation than are some herbs. Also, herbs are more damaged by EtO treatment. Herbs are more sensitive to treatment of any kind. At the doses required to control microbial contamination, insects and other pests will be killed in all life stages. Radiation treatment results in cleaner, better quality herbs and spices compared to fumigation with EtO. While both decontamination and sterilization methods result in some changes to some spices, radiation does not change the sensory or functional properties to the same extent as does EtO [12]. This is an important consideration when exporting these products.

6. POLLUTION CONTROL

Municipal and industrial activities of man have led to environmental degradation. The pollutants emitted to the atmosphere are off-gases from industry, power stations, residential heating systems and vehicles. Fossil fuels, which include coal, natural gas, petroleum, shale oil and bitumen, are the main source used to generate heat and electrical energy. Ironically, coal, which is the dirtiest fuels among hydrocarbons, will be the main fossil fuel for the next two centuries [13]. All of these fuels contain major constituents (carbon, hydrogen, oxygen) as well as other materials, such as metals, sulfur and nitrogen compounds. During the combustion process, different pollutants as fly ash, sulfur oxides (SO_2 and SO_3), nitrogen oxides ($NO_x = NO_2 + NO$) and volatile organic compounds, are emitted. Fly ash contains different trace elements (heavy metals). The gross emission of pollutants is tremendous on a worldwide basis. These pollutants remain present in the atmosphere under such conditions that they can effect man and his environment. Air pollution, caused by particulate matter and other pollutants, not only directly affects the environment, but also contaminates water and soil and leads to their degradation. Wet and dry deposition of inorganic pollutants leads to the acidification of environment. These phenomena all affect human health, increase corrosion, and destroy plants and forests. As a result, widespread forest damage has been reported in Europe and in North America. Many cultivated plants are not resistant to these pollutants either, especially in their early period of vegetation.

Mechanisms of pollutant transformation in the atmosphere are described by environmental chemistry. Photochemistry plays an important role in these transformations. SO_2 and NO_x are oxidized, sulfuric and nitric acids are formed in the presence of water vapor, fog and water droplets. Another problem caused by human activities is the emission of volatile organic compounds to the atmosphere. These emissions cause stratospheric ozone layer depletion, ground level photochemical ozone formation, and toxic or carcinogenic human health effects, which contribute to the global greenhouse effect, and accumulate and persist in the environment. Waters in open and underground reservoirs are being polluted, cultivated soil and forests degraded. Most of the plants, especially coniferous trees, are not resistant to the sulfur oxides discharged from municipal and industrial facilities. Water pollution had been primarily a local problem, with identifiable sources of pollution from liquid waste. Until a few decades ago, most of the wastes discharged into waters came from animal and human excreta and from other organic components from industry. In areas with low population density and without sewerage systems, such problems were alleviated to a great extent by the natural self-purification capacity of the receiving water. However, with the increasing urbanization of the last two centuries and a subsequent expansion of sewerage systems without any or adequate treatment, liquid waste loads have become so large that the self-purification capacity of receiving water downstream of large human settlements can no longer prevent adverse effects on water resources. Another problem concerns industrial effluents, which carry chemical contaminations, heavy metals, organic pollutants, often petrochemicals, pesticides, dyes, *etc*. Some pollutants are synthesized *in situ*, as, for example, chloroorganic compounds originate from chlorine use for water/wastewater disinfection. The result of discharging such materials include dyeing living water reservoirs and their inhabitants, the risk of infection, health effects caused by contaminated drinking water and offensive smells. Over the years, the pollution load on most receiving waters has further increased. In addition to the impacts from point sources, pollution from non-point (diffuse) sources, for example, leaching and runoff from agricultural areas and long-range transported air pollutants, have become increasingly important. Consequently, the associated problems are no longer just local or regional, but have become continental in scope. The situation regarding environment contamination is becoming critical. Economic and technically feasible technologies for pollution control of gaseous and liquid effluents are being sought. Radiation offers an advanced solution to these problems as well. Radiation technology may greatly contribute to the environmental protection [13]. Industrial electron beam installations for flue gases containing SO_x and NO_x treatment have been already built in China and Poland. The same technology for high sulfur and high humidity off-gases (low quality lignite) has been successfully tested in an industrial pilot plant in Bulgaria. Pilot plant tests performed in Japan have illustrated that by using electron beam for municipal waste incinerator off-gas treatment the concentration of dioxins can be reduced by 80%, other persistent organic pollutants can be depleted as well. The positive results the electron beam wastewater treatment are the basis for a full-scale industrial plant being built in the South Korea. A pilot gamma plant for sludge irradiation, producing a high-grade organic fertilizer, is in operation in India.

In most of continuous flow systems (flue gases, wastewater) electron accelerators are being used [14].

6.1. GASEOUS POLLUTANT EMISSION CONTROL

Different air pollution control technologies are being sought. The conventional technologies most often used for air pollution control are: (i) wet flue gas desulfurization (FGD), based on SO_2 absorption in lime or limestone slurry; and (ii) selective catalytic reduction (SCR), based on NO_x reduction over a catalyst to atmospheric nitrogen with ammonia as the reductive specie. However, technologies which treat different pollutants in one step are of special interest. Electron beam flue gas treatment (EBFGT) technology is such a process. EBFGT technology is among the promising advanced technologies. It is a dry-scrubbing process for the simultaneous SO_2 and NO_x removal, where no waste is generated. After the irradiation of the polluted gas, fast electrons interact with the gas, creating various ions and radicals, and the primary species formed include e^-, N_2^+, N^+, O_2^+, O^+, H_2O^+, OH^+, H^+, CO_2^+, CO^+, $N_2^\bullet$, $O_2^\bullet$, N, O, H, OH, and CO. In the case of high water vapor concentration, the oxidizing radicals $^\bullet OH$ and $HO_2^\bullet$ and excited ions such as O(3P) are the most important products. The SO_2, NO, NO_2, and NH_3 present cannot compete with the reactions because of their very low concentrations, but will react with N, O, $^\bullet OH$, and $HO_2^\bullet$ radicals. Ammonia, as mentioned above, is added to the gas to neutralize the acids formed in these reactions, with an aerosol of ammonium sulfate and ammonium nitrate being the final products of the reaction. In this technology, the temperature and humidity of flue gas are modified in the spray cooler, then almost stoichiometric amounts of ammonia is added to the flue gas and such a gas mixture is irradiated in the process vessel by an electron beam from

Fig.4. ELV-12 accelerator for environmental applications.

accelerator. The by-product is collected by the electrostatic precipitator (ESP) and may be used as an agricultural fertilizer or as a component of NPK (nitrogen-phosphorus-potassium) or NPKS (nitrogen-phosphorus-potassium-sulfur) commercial fertilizer. This technology was implemented in a full-industrial scale at the Electric Power Station (EPS) "Pomorzany" in Szczecin for the purification of flue gases emitted from two low-sulfur coal-fired Benson boilers. In this industrial plant with a nominal flow rate of 270 000 Nm^3/h, SO_2 and NO_x are removed from flue gas with the efficiency exceeding 90 and 70%, respectively [15]. A problem in implementing this technology was the need for reliable high power, mid-voltage, self-shielded accelerators. A new unit manufactured by the Budker Institute of Nuclear Physics in Novosybirsk, Russia, and EB Tech Co., Ltd., Republic of Korea, meets these requirements. The ELV-12 accelerator provides a 0.6 to 1.0 MeV electron beam and power that is equal to 400 kW, as shown in Fig.4.

Fig.5. Pilot plant at oil refinery: 1 – stack of F 1001 boiler, 2 – boiler F 1001, 3 – flue gas duct, 4 – pilot plant control room, 5 – gas conditioning column, 6 – pilot plant stack, 7 – cartridge bag filter, 8 – thermal insulated duct, 9 – cyclone, 10 – ammonia dosing unit, 11 – mobile accelerator unit.

A new use of concern is the treatment of flue gas from oil fired boilers [16] and diesel engines on cargo ships. The pilot plant for the use of EBFGT from an oil fired boiler was constructed in a refinery, using EB a mobile unit manufactured by EB Tech Co., Ltd., as shown in Fig.5. Tests have proved a high removal efficiency of pollutants in this case as well.

6.2. WASTEWATER POLLUTANTS DISCHARGE CONTROL

Because of the increasing levels and complexity of polluted effluents from municipalities and industry, current wastewater treatment technologies may not be successful for the remediation of polluted waters and for disinfection. The development and implementation of alternative technologies for the cleanup of industrial wastewater, municipal water, groundwater, and drinking water are critical to sustainability in many countries. Research and development work using a large scale wastewater treatment facility was performed at the Miami Electron Beam Research Facility. The water purification process relied on water radiolysis to degrade pollutants. Some of the free radicals formed are oxidative species ($^{\bullet}OH$), and the others reductive (H, e^{-}_{aq}). Thus, there is competition between oxidation and reduction processes in the system. A possible synergistic effect with ozone may improve the overall efficiency of the destruction of organic pollutants. In this case, ozone would react with the strong reductive species leading to the formation of hydroxyl radicals. Aqueous effluents that have been treated by irradiation include polluted drinking water and liquid industrial and agricultural wastes. The formation of some possible toxic by-products could limit implementation of this process. An industrial plant has been constructed in the Republic of Korea. Based on the data obtained in the laboratory and from pilot plant experiments, suitable doses were determined to be around 0.2 kGy for a flow rate of 10 000 m^3 of effluent per day. In this case, a high power accelerator (1 MeV, 400 kW) manufactured by the EB Tech Co., Ltd. was used. High energy electron disinfection of sewage wastewater in flow streams has been proposed and tested. The hybrid use of controlled chemical-oxygen-demand (COD) and microbiological load with electron beam processing looks the most promising for future use.

Another use for accelerator-generated electron beams is the degradation of antibiotics and leftover drugs that are in liquid effluents. Antibiotics for animal husbandry, administered drugs, metabolites, or their degradation products enter the ecosystem *via* the use of manure or slurries on areas used for agricultural purposes or from pasture-reared animals that excrete directly onto the land. The degradation of ampicillin in a pig manure slurry and an aqueous ampicillin solution have been studied using electron beam irradiation. The results demonstrate that EB technology is an effective means of removing antibiotics from manure and bodies of water.

6.3. SOLID WASTE TREATMENT

The problem of water contamination by chemical and biological matter is well known. In many regions there are deficits in the water supply for municipal, agricultural, and industrial use. Water in reservoirs, drawn mainly from rivers, is reused many times. The purification and disinfection of water is needed to protect the health of consumers. Even so, bottled water and household filters are very popular as a source of quality drinking water. The most popular and efficient wastewater purification systems are biological treatment plants. These plants then become a source for biological sludge, which is a waste that contains approximately 3% solids of higher if a dewatering process is used. Unfortunately, the sludge of municipal wastewater origin is biologically contaminated by viruses, bacteria, and the eggs of parasites. In the case of landfill disposal, these contaminants survive for many years. Even in regions with severe winters, the sludge undergoes continuous fermentation and the temperature is higher than the freezing point of water. Some years ago, different countries solved this problem by dumping such wastes into the sea, which is now prohibited. The sludge is a good organic fertilizer and is especially good for use with sandy soils. Some countries are using injection under the soil, which is not so safe from a health point of view if the field is used for the cultivation of food crops. In the European Union, sludge incineration is the current direction taken to solve this problem. However, all combustion processes emit pollutants and greenhouse gases to the atmosphere. Different methods of disinfection have been proposed: heat pasteurization, mixing with lime, and ionizing radiation treatment. The destruction of the microbes by radiation is achieved by direct and indirect DNA double- and single-strand breaks and other damage to cell components. Again, due to the high concentration of water in a living organism, the free radicals formed play a most important role in the indirect damage to the living organism's structure. The indirect action of ionizing radiation, which is very similar to that discussed earlier for nonliving physicochemical matter, involves water radiolysis and the effect of active species on DNA. Research has shown that sewage sludge can be disinfected successfully by exposure to high energy radiation. Doses of 2 to 3 kGy destroy more than 99.9% of bacteria present in sewage sludge. Higher doses (up to 10 kGy) are required to inactivate more radiation-resistant organisms. Both gamma sources (cobalt-60, cesium-137) and electron accelerators can be used for the irradiation of sewage sludge. Gamma source radiation has better penetration, allowing thicker layers of sludge to be irradiated, although they have less power and require a longer irradiation time than do electron sources. The irradiated sludge, being pathogen-free, can be beneficially used as manure in agricultural fields as it is rich in nutrients required for soil. Initial field trials of sludge as manure in agricultural fields used for winter wheat crops as well as for summer green grain crops have been very encouraging. Since the irradiated sludge is free from bacteria, it can also be used as a medium for growing bacteria that is useful for the soil like rhizobium and azotobacter and to produce biofertilizers, which can be used to enhance crop yields. In the case of sludge or soil irradiation, high energy accelerators are preferable. An accelerator of 10 MeV at 10 kW is able to irradiate 70 tons of sludge a day at a dose of 5 to 6 kGy. The estimated cost of such installation is US$4 million.

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