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PROCEEDINGS

Application of ionizing radiation to environment protection

Andrzej G. Chmielewski

Abstract Radiation technology may contribute to the environmental protection to a great extent. Electron beam industrial installations for flue gases containing SO_x and NO_x treatment have been already built in China and Poland. The same technology for high sulphur 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 applying electron beam for municipal waste incinerator off-gases treatment the concentration of dioxins can be reduced by 80%, other persistent organic pollutants can be depredated as well. The positive results of 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. All these achievements are reported in this paper.

Key words electron accelerator • gamma rays • flue gas • wastewater • sludge

A. G. Chmielewski
Faculty of Process and Chemical Engineering,
Warsaw University of Technology,
1 L. Waryńskiego Str., 00-645 Warsaw, Poland
and Institute of Nuclear Chemistry and Technology,
16 Dorodna Str., Warsaw, Poland,
Tel.: +48 22-504 1058, Fax: +48 22-8111532,
E-mail: a.chmielewski@ichtj.waw.pl

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Introduction

Municipal and industrial activities of man lead to environment degradation. The pollutants are emitted to the atmosphere with 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 of heat and electrical energy. Ironically, coals, which are the dirtiest fuels among hydrocarbons, will be the main fossil fuel for the next two centuries [33].

All these fuels contain major constituents (carbon, hydrogen, oxygen) as well as other materials, such as metals, sulphur and nitrogen compounds. During the combustion process different pollutants as fly ash, sulphur 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). Gross emission of pollutants is tremendous worldwide. These pollutants are present in the atmosphere in such conditions that they can affect man and his environment.

Air pollution, caused by a particulate matter and other pollutants, not only affects directly on 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 affect human health, increase corrosion, and destroy plants and forests. Widespread forest damages have been reported in Europe and North America. Many cultivated plants are not resistant to these pollutants either, especially in the 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, sulphuric and nitric acids, which are formed in the presence of water vapour, fog and 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, accumulate and persist in the environment [4].

Waters in the open and underground reservoirs are being polluted, cultivated soil and forests degraded. Most of the plants, especially coniferous trees, are not resistant to sulphur oxides discharged from municipal and industrial facilities. Water pollution used to be primarily a local problem, with identifiable sources of pollution by liquid waste. Up to a few decades ago most of the wastes discharged to waters came from animal and human excreta and other organic components from industry.

In areas with low population density and without sewerage systems such problems are alleviated to a great extent by the natural self-purification capacity of the receiving water. However, with 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.

An other problem concerns industrial effluents, which carry out chemical contaminations, heavy metals, organic pollutants, most often petrochemicals, pesticides, dyes, etc. Some pollutants are synthesized *in situ*, as, for example, chloroorganic compounds originating from chlorine application for water/wastewater disinfections. The results of discharges of such materials include dyeing living water reservoirs, inhabitants, risk of infection, health effects caused by contaminated drinking water and offensive smells. Over the years, the pollution load of most receiving waters has further increased. In addition to 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 [13].

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. Therefore, economically and technically feasible technologies for pollution control, gaseous and liquid effluents streams are searched for. Radiation offers advanced solutions to the selected problems as well [10, 31].

Radiation processing of gaseous systems

Wet flue gas desulphurisation (FGD) and selective catalytic reduction (SCR) can be applied for flue gas treatment and SO_2 and NO_x emission control. Volative organic compounds (VOC) are usually adsorbed on carbon, but this process is rarely used for lean hydrocarbon concentrations up to now. All these technologies are complex chemical processes, and wastes, like wastewater, gypsum and used catalyst, are generated [35].

Electron beam technology is among the most promising advanced technologies of new generation. This is a dry-scrubbing process of simultaneous SO_2 and NO_x removal, where no waste except the by-product is generated. Researches show that irradiation of flue gases with an electron beam can bring about chemical changes that make removal of sulphur and nitrogen oxides easier. The main components of flue gases are N_2, O_2, H_2O, and CO_2, with much lower concentration of SO_x and NO_x. NH_3 may be present as an additive to aid removal of the sulphur and nitrogen oxides. Radiation energy is absorbed by gas components in proportion to their mass fraction in the mixture. The fast electrons slow down, and secondary electrons are formed which play an important role in the overall energy transfer.

After irradiation, fast electrons interact with gas generating various ions and radicals. Primary species formed include e^-, N^{2+}, N^+, O^{2+}, O^+, H_2O^+, OH^+, H^+, CO_2^+, CO^+, N_2^*, O_2^*, N, O, H, OH, and CO. In the case of high water vapour concentration, the oxidizing radicals $OH^\bullet$ and $HO_2^\bullet$ and excited ions as O(3P) are the most important products. These species take part in a variety of ion-molecule reactions, neutralization reactions, and dimerization [29].

The SO_2, NO, NO_2, and NH_3 present cannot compete with the reactions because of very low concentrations, but react with N, O, OH, and HO_2 radicals.

After humidification and lowering its temperature, flue gases are guided to a reaction chamber, where irradiation by electron beam takes place. Ammonia is injected upstream the irradiation chamber. There are several known pathways of NO oxidation. In the case of electron beam treatment the most common are [25]:

$$NO + O(^3P) + M \rightarrow NO_2 + M \quad (1)$$

$$O(^3P) + O_2 + M \rightarrow O_3 + M \quad (2)$$

$$NO + O_3 + M \rightarrow NO_2 + O_2 + M \quad (3)$$

$$NO + HO_2^\bullet + M \rightarrow NO_2 + {}^\bullet OH + M, \quad (4)$$

where M is any inert molecule.

After oxidation, NO_2 is converted to nitric acid in the reaction with $OH^\bullet$ according to the reaction:

$$NO_2 + {}^\bullet OH + M \rightarrow HNO_3 + M \quad (5)$$

HNO_3 aerosol reacts with NH_3 giving ammonium nitrate according to the reaction:

$$HNO_3 + NH_3 \rightarrow NH_4NO_3 \quad (6)$$

NO partly is reduced to atmospheric nitrogen.

There can be also several pathways of SO_2 oxidation depending on the conditions. In the electron beam treatment, the most important pathways are radio-thermal and thermal reactions [36].

Radio-thermal reactions proceed through radical oxidation of SO_2 in the reaction:

(7) $SO_2 + {}^{\bullet}OH + M \rightarrow HSO_3 + M$

Then, HSO_3 generates ammonium sulphate in the following steps:

(8) $HSO_3 + O_2 \rightarrow SO_3 + HO_2$
(9) $SO_3 + H_2O \rightarrow H_2SO_4$
(10) $H_2SO_4 + 2NH_3 \rightarrow (NH_4)_2SO_4$

The thermal reaction is based on the following process:

(11) $SO_2 + 2NH_3 \rightarrow (NH_3)_2SO_4$

(12) $(NH_3)_2SO_2 \xrightarrow{(O_2,H_2O)} (NH_4)_2SO_4$

The total yield of SO_2 removal (η) consists of the yield of thermal (η_1) and radio-thermal (η_2) reactions that can be written [3, 24]:

(13) $\eta SO_2 = \eta_1(\phi,T) + \eta_2(D,\alpha NH_3,T)$

The yield of the thermal reaction depends on the temperature and humidity. It decreases with increasing temperature. The yield of radio-thermal reaction depends on the dose, temperature and ammonia stoichiometry. The main parameter in NO_x removal is the dose. The rest of parameters play a minor role in the process. Nevertheless, in real industrial process, dose distribution and gas flow conditions are important from the technological point of view [7]. To achieve reduction of energy consumption, a combined electron beam/microwave (EB/MW) process has been investigated [32].

Radiation treatment of SO_2 and NO_x

Japanese scientists demonstrated in 1970–1971 the removal of SO_2 using an electron beam from a linear accelerator (2–12 MeV, 1.2 kW). A dose of 50 kGy at 100°C led to the conversion of SO_2 to an aerosol of sulphuric acid droplets, which were easily removed [23].

Ebara Co. used an electron accelerator (0.75 MeV, 45 kW) to convert SO_2 and NO_x into a dry product containing $(NH_4)_2SO_4$ and $(NH_4)_2SO_4 \cdot NH_4NO_3$ which could be used as a fertilizer. Using the 'Ebara process', two larger scale pilot plants were constructed in Indianapolis, USA [14] and Karlsruhe, Germany [37]. The Indianapolis plant was equipped with two electron beam accelerators (0.8 MeV, 160 kW) and had a capacity of $1.6–3.2 \times 10^4$ m^3/h with gas containing 1000 ppm SO_2 and 400 ppm NO_x. In Karlsruhe, two electron accelerators (0.3 MeV, total power 180 kW) were used to treat $1–2 \times 10^4$ m^3/h flue gas containing 50–500 ppm of SO_2 and 300–500 ppm of NO_x.

However, the final engineering design technology for industrial applications was achieved at pilot plants operating in Nagoya, Japan [27] and Kawęczyn, Poland [8]. In the case of the latter, new engineering solutions were applied; double-longitudinal gas irradiation, an air curtain separating the secondary window from corrosive flue gases and modifications of humidification/ammonia system (high enthalpy water or steam injection, ammonia water injection) and others. The obtained results (Fig. 1) have confirmed physicochemistry of the process, which was discussed earlier. A high dose is required for NO_x removal, while SO_x is removed in proper conditions at low energy consumption.

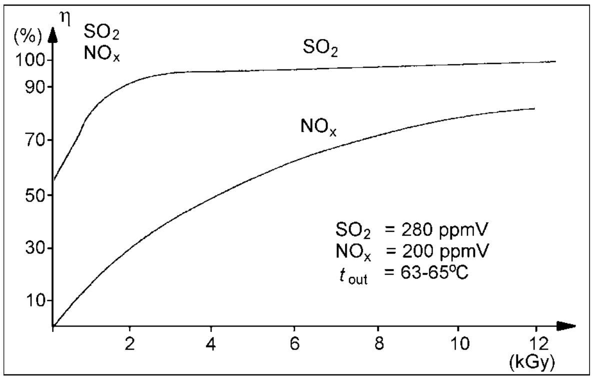

Fig. 1. SO_2 and NO_x removal efficiency *vs.* dose. The results obtained in the pilot plant experiments.

These new solutions led to the economical and technical feasibility improvement and final industrial scale plant construction. Ebara Corporation has constructed a full scale plant in Chengdu, China, mostly for SO_x removal, therefore, the power of accelerators applied is 320 kW for treatment of 270,000 cubic meters per hour of the flue gas. Reported efficiency is 80% for SO_x and 20% for NO_x [12].

The flue gas treatment industrial installation is located in the EPS Pomorzany in Szczecin in the north of Poland [5]. The installation purifies flue gases from two Benson boilers of 65 MW_e and 100 MWth each. The maximum flow rate of the gases is 270,000 Nm^3/h and the total beam power exceeds 1 MW. There are two reaction chambers with nominal flow gas rate of 135,000 Nm^3/h. Each chamber is irradiated by two accelerators (260 kW, 700 keV), which are installed in series. The applied dose is in the range of 7–12 kGy. The removal of SO_2 approaches 80–90% in this dose range, and that of NO_x is 50–60%. The by-product is collected by the electrostatic precipitator and is shipped to a fertilizer plant.

The installation consists of four main parts:
– flue gas conditioning unit,
– ammonia storage and dosage unit,
– reaction chambers,
– by-product collecting and storage unit.

A scheme of the installation at EPS Pomorzany is presented in Fig. 2.

As it was previously mentioned, the removal efficiency depends strongly on the process conditions. The highest obtained efficiency for SO_2 reaches 95%, while for NO_x it reaches 70% (Fig. 3). The obtained results may be compared with those previously reported, based on the pilot plant experiments and theoretical calculations, presented in Fig. 1. Very good agreement between the results obtained may be noticed.

The data obtained during the operation of the installation confirmed the previously assumed theses on the impact of the process parameters on the removal effectiveness. In the case of NO_x removal the most important parameter is the dose. The inlet concentra-

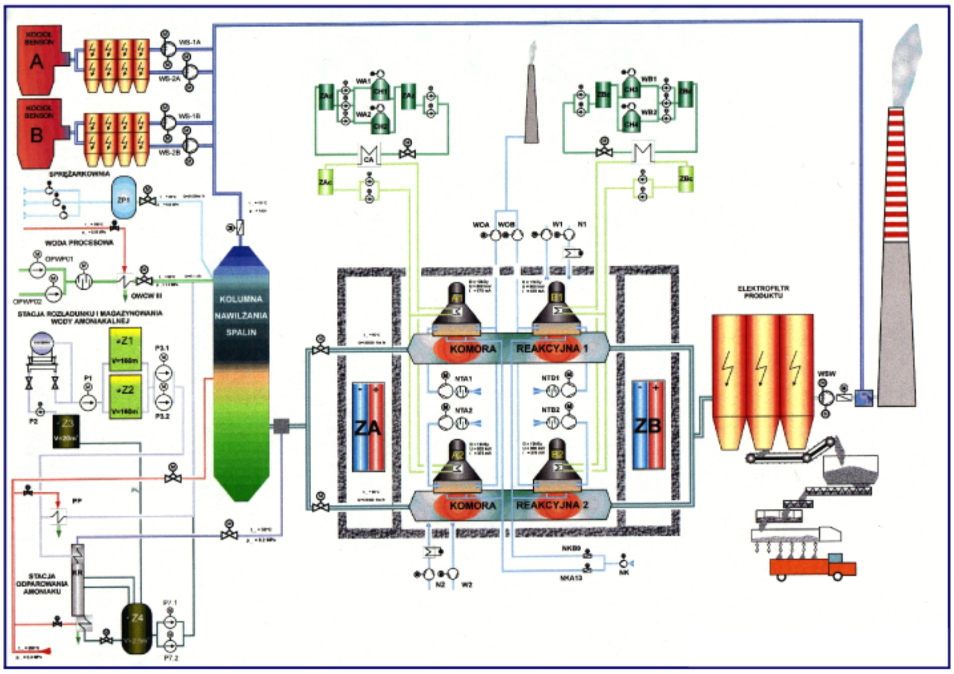

Fig. 2. A scheme of the industrial plan for electron beam flue gas treatment at EPS Pomorzany, Poland.

tion of NO_x is the second parameter. The impact of these parameters on the pollutant removal was observed. The correlation is linear and the total removal (taken in mg/Nm^3) increases with inlet concentration of NO_x, while the relative removal (in %) decreases with increasing this parameter. The ammonia stoichiometry factor has very little impact on the NO_x removal.

In the case of SO_2 removal there are more parameters, which affect the pollutant removal efficiency. The most important among them is the temperature of the gas down stream humidification tower due to the contribution of thermal reactions. Afterwards, the dose should be mentioned. Although the humidity seems to have the major impact on the process efficiency, it is hard to prove it with no doubt because of the strong correlation between the humidity and the temperature of the process (dew point depends on both parameters: humidity and temperature). During the water evaporation process, the temperature decreased and the humidity increased. A strong influence of ammonia stoichiometry

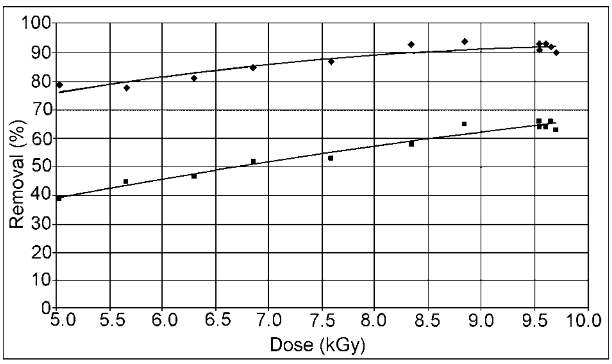

Fig. 3. SO_2 and NO_x removal efficiency *vs.* dose. The results were obtained in an industrial installation. (SO_2 inlet conc. 1500–1630 mg/Nm^3, NO_x inlet conc. 470–540 mg/Nm^3.)

ratio on the SO_2 removal efficiency has been observed. The other factors as flue gas flow rate and inlet concentration have a much less impact on the removal efficiency. During the experiments, one more parameter having impact on the whole process, has been detected: the ammonia injection mode. It was observed that the injection of the part of ammonia water directly to the humidification tower increased the SO_2 removal efficiency. This phenomenon is under investigation now.

The pilot plant for the treatment of high-sulphur coal lignite fired boiler off-gases has been constructed at the Maritsa 2 East Thermal Power Station in Bulgaria. For high SO_x and humidity flue gases, high efficiencies of SO_x and NO_x removal have been reported.

Radiation induced VOC removal from off-gases

In the case of VOCs decomposition, the process itself is based on similar principles as primary reactions concerning SO_2 and NO_x removal, i.e. free radicals attack organic compounds chains or rings causing VOCs decomposition [6].

For chlorinated aliphatic hydrocarbon decomposition (e.g. chloroethylene), Cl-dissociated secondary electron-attachment and Cl, OH radicals reaction with VOCs plays a very important role for the decomposition of VOCs.

For aromatic hydrocarbons, the decomposition of VOCs will mainly go through:

Positive ion charge transfer reactions

(14) $M^+ + RH$ (RH = VOC, e.g. benzene or PAHs) $= M + RH^+$

Because RH has lower ionization energy (IE) (benzene: IE = 9.24 eV; PAHs: IE < 10 eV) than most of the primary positive ions (IE > 11 eV) formed above, part of VOC will be decomposed by rapid charge transfer reactions.

Radical – neutral particle reactions

The OH radical plays a very important role in the VOC decomposition, especially when water concentration is higher than 10%. $^{\bullet}OH$ radicals react with VOC in two wys:

$^{\bullet}OH$ radical addition to the aromatic ring (e.g. toluene)

(15) $^{\bullet}OH + C_6H_5CH_3 = R1^{\bullet}$

and H atom abstraction (for the alkyl-substituted aromatic compounds) or H atom elimination (for benzene, naphthalene and the higher polycyclic aromatic hydrocarbons)

(16) $C_6H_5CH_3 + {^{\bullet}OH} = R2^{\bullet} + H_2O$
(H atom abstraction)
(17) $C_6H_6 + {^{\bullet}OH} = C_6H_5OH + H$
(H atom elimination)

Radicals ($R1^{\bullet}$, $R2^{\bullet}$) formed above go though very complex reactions: O_2 addition, O atom release, aromatic -CHO (-dehydes), -OH (-ol) compounds formed or ring cleavage products:

(18) $R^{\bullet}\ (R1^{\bullet}, R2^{\bullet}) + O_2 = RO_2^{\bullet}$
(19) $2RO2^{\bullet} = 2RO^{\bullet} + O_2$
(20) $RO2^{\bullet} + NO = RO^{\bullet} + NO_2$
(21) $RO^{\bullet} + O_2 = HO_2^{\bullet}$ + products
(aromatic-CHO, -O)
(22) $RO^{\bullet} \rightarrow$ aliphatic products

The possibility of the process application for dioxins removal from off gases has been studied [21, 28] and recent pilot studies demonstrated that the process is technically and economically feasible [20].

Radiation processing of aqueous system

Irradiation of water with ionizing radiation produces ionized and excited water molecules and free electrons. The excited water molecules quickly return to the ground state. Ionized molecules react in liquid water to form hydroxyl radicals, OH,

(23) $H_2O^+ + H_2O \rightarrow H_3O^+ + OH^{\bullet}$

The free electrons become hydrated

(24) $e^- + nH_2O \rightarrow e^-_{aq}$

The radicals react between themselves or with hydrogen ion (H_3O^+) to form molecules H, HO and H. The yield of radicals and molecular products depends on pH. At low pH, hydrated electrons react with hydrogen ion (H_3O^+ or H^+) to form hydrogen atom

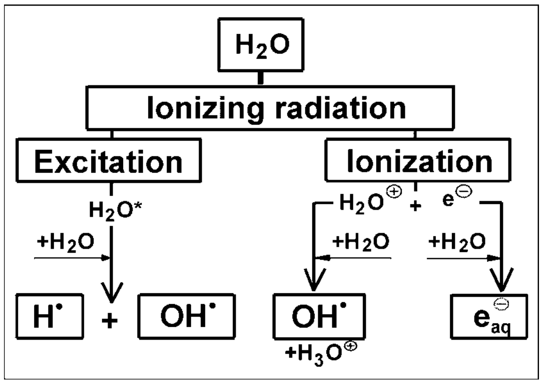

Fig. 4. Water radiolysis: formation of free radical species in water by means of ionizing radiation.

Table 1. Fundamental reactions for OH radicals generation in different advanced oxidation processes

UV-radiation of aqueous solutions	Electron beam irradiation of aqueous solutions
$O_3 \xrightarrow{h\nu} O + O_2$ $O + H_2O \rightarrow H_2O_2$ $H_2O_2 \rightleftharpoons HO_2^{\ominus} + H^{\oplus}$ $O_3 + HO_2^{\ominus} \rightsquigarrow OH$ $H_2O_2 \xrightarrow{h\nu} 2\,OH$	$H_2O \xrightarrow{e^{\ominus}} \begin{cases} H_3O^{\oplus};\ OH^{\ominus} \\ \boxed{OH;\ e^{\ominus}_{aq};\ H} \\ H_2;\ O_2;\ H_2O_2 \end{cases}$ $O_3 + \begin{cases} e^{\ominus}_{aq} \\ H \\ H_2O_2 \end{cases} \rightsquigarrow OH$
Radiation is absorbed by solutes not water! Always just one source for OH (O_3 and H_2O_2, resp.).	Radiation is absorbed by water not by solutes! Two sources for OH (water radiolysis and O_3 decomposition).

(25) $e^-_{aq} + H_3O^+ \rightarrow H_2O + H$

Radical products are highly reactive and are responsible for most of the chemical reactions when aqueous solutions are irradiated. A scheme of the process is given in Fig. 4 [16].

A comparison of processes induced by UV and electron beam irradiation is presented in Table 1.

Radiation purification of drinking water and wastewater

Contamination of surface water and groundwater from industrial waste and anthropogenic activities is a serious problem in many countries. The wide application of fertilizers, pesticides, fungicides can lead to ground water pollution and consequent contamination of drinking water. Population growth and declining fresh water supplies make a need for clean water to be one of the critical challenges for the 21st century. Because of the increasing levels and complexity of polluted effluents from municipalities and industry, current wastewater treatment technologies are often not successful for the remediation of polluted waters and disinfection.

The development and implementation of alternative technologies for the clean up of industrial wastewater, municipal water, groundwater and drinking water is critical to the sustainability of many countries. Among the possible water treatment alternatives radiation processing, a very effective form of energy use, can degrade toxic organic compounds and biological contaminants. Prof. Pikaev [30] was a pioneer in the development of this technology. Furthermore, important research has been performed at a Miami pilot facility [22].

Aqueous effluents that have been treated by irradiation include polluted drinking water, liquid industrial and agricultural wastes. However, attention must be paid to the toxicity of the by-products formed in the process which is the main limitation of its implementation. This is the major factor which has to be carefully studied during the implementation of all advanced oxidation technologies (ozone, ozone + TiO_2, UV) [17]. The differences and similarities of UV and EB water treatment mechanisms are given in Table 1 [15]. The industrial effluents contain a variety of pollutants at high concentrations, and substances that are toxic or difficult to destroy such compounds as salts of mercury and bismuth, cyanides, phenols and dyes. To remove such pollutants by irradiation treatment, high doses are generally required and combined processes, which have been developed in a combination with conventional processes such as chemical, biological, or thermal treatment, floatation, and others, should be applied. Only few full-scale applications are available.

When water containing humic substance is treated with chlorine, carcinogenic chlorinated organic compounds are formed. Studies suggest that a comparatively low dose of 1 kGy will bring about decolourisation, deodorization, and disinfection of natural water and dechlorination of organic chlorocompounds present at low concentrations [1].

An electron accelerator (0.7–1 MeV, 50 keV) was applied at a Voronezh rubber plant in Russia to convert the non-biodegradable emulsifier Nekal in a plant waste into the biodegradable form. The dose required to decompose 10^{-3} mol/dm^3 Nekal in aqueous solution was 300 kGy. The plant had two production lines and could treat up to 2×10^3 m^3 of effluent per day [2].

The most promising achievements were achieved recently in South Korea, where a pilot plant is in operation [38].

A pilot plant (output 1000 m^{3}day^{-1}) with an ELV electron accelerator (energy 1 MeV, beam power 40 kW) is in operation since October 1998. Combined electron-beam and biological treatment was used for the purification of dyeing complex wastewater under continuous flow conditions. The main results of pilot-scale experiments consisted, in fact, that a decrease in total content of pollutants after biological treatment was substantially influenced by a preliminary electron-beam treatment (mainly, because of radiolytic conversions of terephthalic acid which is the main pollutant of wastewater). The reduction of non-biodegradable COD (chemical oxygen demand) into biodegradable BOD (biological oxygen demand) compounds was achieved. An equal purification degree corresponded to 17 hours of bio-treatment without preliminary irradiation and about 8 hours of bio-treatment with preliminary electron-beam treatment at an absorbed dose of 1–2 kGy.

An industrial plant is being constructed. Based on the data obtained in the laboratory and pilot plant experiments, suitable doses are determined as being around 0.2 kGy for a flow rate of 10,000 m^3 effluent per day. Therefore, accelerator with the power of 400 kW is applied for economies and compactness of the plant.

The actual operation cost for 100,000 m^3/day plants is 430,000 $US/yr, and, if we consider the interest and depreciation of investment, the cost comes up to around 1 $USM/yr. It is approximately 0.12 $US/m^3 for the construction and 0.03 $US/m^3/yr for operation, so it is inexpensive as compared to other advanced oxidation techniques such as ozonation, UV techniques etc.

Radiation induced removal of heavy-metal ions from water

Toxic metals from industrial effluent streams include heavy metals such as lead, mercury, cadmium, nickel, silver, zinc, and chromium. These heavy metals are accumulated in soil and eventually are transferred into human food chain [34]. Ionizing radiation of aqueous solutions generates free radicals, radical ions and stable products:

(26) $H_2O \rightarrow e^-_{aq}, H; OH, H_2O_2, H_2, H_3O^+$

with yields (G value) of $0.28(e^-_{aq})$, 0.062(H); 0.28(OH), $0.072(H_2O_2)$, $0.047(H_2)$ in units of μmol/J.

The hydrated electron e^-_{aq} is the strongest reducing agent.

(27) $e^-_{aq} + H_3O^+ \rightarrow H^\bullet + H_2O$

Cr(V) is unstable and is further reduced to the stable Cr^{3+} ions

(28) $Cr(VI) + H^\bullet \rightarrow Cr(V)$

Lead can also be reduced by $H^\bullet$ atoms

(29) $Pb^{2+} + e^-_{aq} \rightarrow Pb^+$
(30) $2Pb^+ \rightarrow Pb + Pb^{2+}$
(31) $H^\bullet + Pb^+ \rightarrow PbH^+$
(32) PbH^+ decays to produce Pb
(33) $2PbH^+ \rightarrow H_2 + Pb^{2+} + Pb$
(34) $HgCl_2 + e^-_{aq} \rightarrow HgCl + Cl^-$
(35) $HgCl_2 + H^\bullet \rightarrow HgCl + Cl^- + H^+$

HgCl is not stable and dimerized to Hg_2Cl_2 as a final insoluble products

(36) $2HgCl \rightarrow Hg_2Cl_2$

The hydroxyl radical ($^\bullet$OH) is one of the powerful oxidizing species, which lead to the transformation of the metal ions to higher valence states [18]. However, due to the fact that normally the concentrations of heavy metals in wastewater are very low (ppms), the process does not seem to be technically feasible, since trace quantities of reduced metals have to be separated by a mechanical way from wastewater. For higher concentrations chemical (precipitation, ion exchange) or physical methods (membranes, electrolysis) are more feasible from economical or technical points of view.

Radiation processing of solid state systems

Municipal sewage and sludge

Electron beam irradiation is a practical and economic method for disinfecting liquid municipal wastes and sludge. Deer Island Electron Research Facility in Boston found a dose of 0.5 kGy to be sufficient to disinfect municipal wastewater effluent and also to decompose organic pollutants. Takasaki Radiation Chemistry Research Establishment found that a dose of about 0.4 kGy was required in order to disinfect raw wastewater prepared by mixing primary and secondary sewage effluents [26].

Research has shown that sewage sludge can be disinfected successfully by exposure to high-energy radiation. At a plant near Munich, doses of 2–3 kGy destroy more than 99.9% of bacteria present in sewage sludge, and at a plant near Boston a slightly higher dose (4 kGy) was used. Higher doses (up to 10 kGy) are required to inactivate more radiation resistant organisms at plants in Albuquerque, USA and Ukraine. Both gamma sources (Co-60, Cs-137) and electron accelerators can be used for irradiation of sewage sludge. Gamma sources have better penetration allowing thicker layers of sludge to be irradiated [9], although they are less powerful and take longer irradiation time than electron sources [19].

The pilot plant using a gamma source is operating in India. The irradiator system can be easily integrated with a conventional treatment plant with flexibility of operation. Various dose treatment can be imparted to sludge with the addition of sensitising agents such as oxygen, air, ozone, etc. The radioactive source loading, unloading or transport is very easy and very safe. It can be accomplished in a day. After augmentation of source strength in the early 2001, 12 cubic meters of sludge is irradiated in one shift (yielding a 5 ton sludge per month). About 3 kGy of absorbed dose in sewage sludge removes 99.99% of pathogenic bacteria consistently and reliably in a simple fashion.

The process of hygenization of sewage sludge using radiation is very simple. The incoming sludge is taken to an underground reservoir. It is then fed to irradiation vessel of 3 m^3 capacity and circulated continuously in a loop for a pre-determined period. After the radiation exposure, the treated sludge is withdrawn from the irradiation vessel and pumped out to drying sand beds where the water evaporates yielding pathogen free dried sludge. The irradiated sludge being pathogen free can be beneficially used as manure in the agricultural fields as it is rich in nutrients required for the soil. The performed initial field trials in villages of Baroda city on sludge as manure in agriculture fields in winter wheat crops as well as in summer green gram crops have been very encouraging and have prompted farmers for putting increasing demands. Since the irradiated sludge is free from bacteria, it can also be used as a medium for growing soil useful bacteria like rhizobium and azetobactor to produce bio-fertilizers, which can be used to enhance the crop yields.

Soil remediation

The US Environmental Protection Agency (EPA) has found that polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) present serious public health risk and set limits on storage, transport, and disposal of waste materials containing dioxins. A limit of 1 ppb has been established for 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD), which is the most toxic member of this family of compounds. Studies have demonstrated that TCDD can be converted to products of neglibible toxicity by radiolysis with gamma rays from cobalt-60. Destruction greater than 98% was achieved with a dose of 800 kGy in a soil contaminated with 100 ppb of TCDD. Addition of contaminants such as dichlorobenzene and hexachlorobenzene did not affect the result. The addition of 25% water and 2.5% nonionic surfactant was beneficial with the model soil [19].

Mail decontamination

Anthrax that was sent in the mail in October 2001 caused several deaths and big economic losses in the USA. Radiation proved to be very effective for mail decontamination. About 4000 tons of letter mail and 200 tons of parcels had been sanitized by the end of 2003 [11].

Conclusions

1. Electron beam flue gas treatment (deSO_x and deNO_x) has been implemented on an industrial scale in Poland and China.
2. Electron beam flue gas treatment has been proven to be effective for VOC and PAH removal. The discussed technology has been tested in industrial conditions for flue gases from a coal fired boiler and an incinerator plant of municipal solid wastes. Toxicity reduction is the efficiency measure to different by-products formed.
3. Regarding the treatment of organic pollutants in the wastewater, similar to other AOT, by-products formed, have to be considered and toxicity tests are the best parameter of the process efficiency. Combined eb/biological process has been studied on a pilot scale in South Korea.
4. Biological contamination control of the secondary effluents seems to be the most promising application at the moment and an industrial plant applying the process is constructed in South Korea.
5. Pilot plant for gamma ray sludge hygenization has been in operation in India for several years. The

technology proved its effectiveness and the product is a fertilizer of good quality.

6. An new application of the technology based on electron accelerators, namely the mail decontamination against bio-terroristic agents was established.

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