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RADIATION PROCESSING OF SEWAGE AND SLUDGE. A REVIEW

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ABSTRACT

This paper describes the potential of using ionizing radiation to disinfect sewage and sludge, as well as the possibilities of recycling natural resources and their by-products. Presented here is a brief review on the development of radiolytic treatment of wastewaters with electron beam accelerators or ^{60}Co gamma sources to eliminate organic and biological contaminants from liquid and solid wastes. Suitable radiation doses are suggested for each particular case.

KEYWORDS: Irradiation, electron beam accelerator, gamma radiation, coliforms, disinfection, sewage, sludge.

I. INTRODUCTION

Global attention to the increasing levels of biohazardous pollutants reaching water, air and soil has led to the necessity of developing new alternative technologies devoted to pollutants degradation. The ability of ionizing radiation to convert non-biodegradable substances to more readily degradable ones and its capacity to eliminate microorganisms can help the treatment of sewage and sludge in near future.

Radiation techniques are well established for sterilization of medical devices and polymer modification. Radiation processing of wastes may be considered a promising technology due to radiations ability to penetrate the material and induce fundamental changes. When sewage is submitted to ionizing radiation field, the following events can be observed: oxidation of organic molecules, disturbance of the structure of organic and inorganic molecules, changes in colloidal systems followed by the killing of microorganisms.

Lowe Jr. *et al.* (1956) carried out one of the first studies applying irradiation to wastewater purification, using a ^{60}Co gamma source irradiator (total activity 10kCi), to disinfect actual effluents. When gamma sources became available during the 60's, a great deal of work was done applying ^{60}Co and ^{137}Cs to hygienize natural water, disinfect sewage and sludge and remove organic compounds from wastewater and industrial effluents.

During the 70's, the first irradiator for disinfection of sewage sludge (4% solids) was installed at Geiselbullach Treatment Plant, Germany. Lessel *et al* (1975) described their experience after the design, installation and operation of the irradiator. In 1978, the United States of America initiated the operation of the Sandia Irradiator for dried sewage solids Sandia Laboratories in Albuquerque, New Mexico. The utilization of another kind of irradiator, the electron beam accelerator, for waste abatement was initiated also during the 70's in the USA. The Massachusetts Institute of Technology developed a program for disinfection of liquid municipal sludge by treatment with energized electrons, Trump (1981). Furthermore, the University of Miami in Virginia Key installed an electron beam machine for disinfection of sludge. It has been used for research and development and also for studying organic effluents removal, Waite *et al.* (1991).

A Workshop on Application of Ionizing Radiation for Decontamination of Environmental Resources, Miami (1994), demonstrated not only the progress of the technology, but also the extensive possibilities of environmental applications. A great deal of work was performed at the facilities of Virginia Key. To point out some of the most recent environmental applications which have been conducted there are: the destruction of hazardous organic compounds in contaminated water, soil, and gaseous waste stream, by Kurucz, C.N. *et al.* (1991); the potential application of this technology for the disinfection of infectious solid and liquid medical wastes, the development of empirical models for estimating the destruction of toxic organic compounds utilizing electrons, by Kurucz, C.N. *et al.* (1995).

As far as electron beam energy is concerned, there are two possibilities of energy utilization. In the first one the electron beam penetrates directly into the exposed material. In the other mode Bremsstrahlung or X-rays are created by interaction of electrons with a high atomic number metal target. Matthews *et al.* (1993) described the behavior of halogenated and nonhalogenated hydrocarbons, contaminants of waterways, groundwater and soil, when submitted to bremsstrahlung radiation produced by four types of accelerators or by using gamma radiation. They also demonstrated the radiolytically induced decomposition of important environmental contaminants such as high explosives and organophosphoric compounds dissolved in water and polychlorinated biphenyls dissolved in oil.

Gehringer *et al.* (1993) combined radiation technology and ozone addition prior to radiation, applying both for remediation of groundwater contaminated by organic solvents, trichloroethylene and perchloroethylene. The addition of ozone improved the generation of the OH radical, enhancing the oxidation of the compounds that contaminate groundwater.

Although radiation technology still occupies a relatively modest position in the industrial and agricultural fields, there exist more than 180 industrial gamma irradiators (^{60}Co) and nearly 1,000 Electron Beam Accelerators, (energy range 0.15 to 10 MeV) operating in the world, Pikaev (1995). Radiation treatment of wastes can be applied to municipal wastewater, sewage sludge, biomedical and hospital wastes, airline wastes, industrial and chemical wastes, flue gases and even for decontamination of soil. In 1992 the American Society of Civil Engineers published "A State-of-the-Art Report", entitled "Radiation Energy Treatment of Water , Wastewater and Sludge", elaborated by the Task Committee on Radiation Energy Treatment, Air and Radiation Management Committee, Environmental Engineering Division and American Society of Civil Engineers. This report discusses the fundamentals of radiation treatment, all types of ionizing radiation, ultraviolet radiation, combined processes, application assessment, including several examples of facilities and recommendations.

Mexico considered the use of ionizing radiation as one of the methodologies to be applied for suitable handling of residual sludge, during the development of a Regional Project for Integrated Study of Residual Sewage Sludge. ^{60}Co gamma rays were applied for disinfection and for organic compound removal, Cruz (1994).

Most of the several hundreds of experiments based on radiation technology applied for sanitary purposes have been performed on a laboratory scale. Concerning economical feasibility, several authors have conducted comparative studies for treatment, using gamma rays and electrons. Hashimoto *et al.* (1991) carrying out an economic study of a radiation-composting plant for sewage, demonstrated that electrons are especially indicated when the facility must be built for large amounts of sludge because the costs gradually decrease with increase of treatment capacity. Suzuki (1992), comparing economics between gamma-rays (^{60}Co) and electrons for a 30.0kGy radiation dose, concluded that gamma irradiation costs about 4 times more than electron irradiation because of the high cost of the facility, the Co-60 source and low productivity.

Among the countries that are considering the possibility of applying radiation for sanitary purposes, we point out: Austria, Canada, USA, Italy, Russia, Japan, Argentina, Mexico and Brazil. The major installations which have contributed to the radiation technology for purifying wastes in the world are presented in Table 1.

The intention of the present paper is to demonstrate the possibilities of some environmental applications and the potential use of radiation or combined processes for desinfection of wastewater. Furthermore some information about irradiator systems as well as the interaction of radiation with water and living cells are briefly reviewed. Particularly the effect of radiation for killing indicator bacteria is discussed regarding some of the results obtained in Brazil.

II. TREATMENT OF WATER AND RADIATION EFFECT ON MICROORGANISMS

The goal of wastewater treatment is to remove solids, chemical organic compounds, metals and biological matter, reaching the limits for regulations in order to guarantee the quality of water. The conventional treatment for sewage effluent basically employs: mechanical filtration, gravity settling, biological oxidation and chemical treatment.

The heterotrofic bacterial flora, inherent from sewage, is indispensable for sanitation since these bacteria oxidize the organic matter but the use of an efficient method for disinfection is essential at the end of the treatment process. The disinfection methodologies widely employ chlorine, but after evidence about the severe effect of chlorine on aquatic organisms, Ward and Grave (1980), and the possibility of generating carcinogenic by-products, much emphasis has been given to the problem of substituting chlorination. When an efficient treatment of the wastewater is applied, the solid fraction remaining, which is referred to as sewage sludge, concentrate the contaminants. Sludge generated in municipal sewage treatment plants is essentially organic, although measurable quantities of metals, minerals and other compounds are present. The management of sludge is one of the big questions to be solved by new alternative technologies, since the annual per capita generation of sludge is approximately 26kg on a dry weight basis. The USA generates annually approximately 6.2 million dry metric tons of sludge (Malina *et* *al* 1993). The options for sludge disposal include high temperature processes (commonly incineration), ocean disposal, controlled land application, and lagooning.

There exists the possibility of recycling sewage sludge as a soil conditioner, after the careful elimination of pathogenic organisms and the control of organic compounds and heavy metals. Sewage sludge contains macronutrients such as nitrogen and phosphorus, essential to plant and animal growth, and micronutrients such as zinc, iron and copper. In this sense, the ability of radiation to reduce biological contamination can be appropriate for decontamination of both sewage and sewage sludge.

Table 1 - Examples of Facilities for Waste Removal by Ionizing Radiation

COUNTRY	RADIATION SOURCE	ENERGY (MeV)	POWER(kW) or ACTIVITY (kCi)	PURPOSE	DOSE (kGy)	REFERENCE
AUSTRIA	EBA	0.5	12.5	TCE,PCE removal	0.2 up to 2.0	12
RUSSIA	EBA	0.7	70	NEKAL Dealkylation, desulfonation	3.0	25
USA	EBA	1.5	75	R&D-Disinfection organic removal	2.0 up to 10	33
JAPAN	EBA	2.0	60	Disinfection - Composting	5.0	13
INDIA	^{60}Co	1.25	150	Disinfection of sludge	5.0	01
GERMANY	^{60}Co	1.25	135	Disinfection of sludge	2.0	19

EBA - Electron Beam Accelerator
Nekal - mixture of isomeric butyl naphthalenesulfonates.

Basic of Radiation Chemistry

At least two basic concepts of radiation chemistry are necessary to recall. The first one is *absorbed dose,* which means the energy absorbed by any material exposed to a radiation field. The absorbed dose or amount of energy absorbed per unit of mass is defined as 1 J/kg, equivalent to 1 Gray. The second concept is the *G-value* which measures the yield of the effect of radiation treatment on the material by the radiation interactions. It expresses the amount of species involved in the irradiation treatment per unit of radiation energy absorbed by the material (e.g., in atoms/100 eV or mol/J).

The radiation chemistry study consists of the experimental determination of the radiation-chemical products, specifying the primary products in the physical stage and following their fate in temporal sequence until observable chemical changes appear. The primary products are usually extremely unstable and initiate a sequence of events. When a mixture of elements or compounds is irradiated by ionizing radiation, the mixture absorbs the energy. From this interaction a mixture of ions, excited molecules. and free radicals are formed as follows:

$AB + e^- \rightarrow AB^* + AB^+ + e^-$ **electronic excitation and ionization;** (1)

$AB^+ + e^- \rightarrow AB^*$ **recombination;** (2)

$AB^* \rightarrow A^\cdot + B^\cdot$ **fragmentation;** (3)

$AB^+ \rightarrow A^+ + B^\cdot$ **fragmentation.** (4)

In the 60's Ballantine (1971) demonstrated, through the radiolysis of water and its generated species, how ionizing radiation interacts with water inducing a reduction in Chemical and Biochemical Oxygen Demand. Based on that sequence of reactions by the interaction of radiation with a molecule of water we can observe:

$H_2O \rightarrow H_2O^*$ (5)

$H_2O^* \rightarrow H^\cdot + OH^\cdot$

$H_2O^+ \rightarrow H_2O^+ + e^-$ (6)

$e^- + \text{water} \rightarrow e^-_{aq}.$

$H_2O^+ + H_2O \rightarrow H_3O^+ + OH^\cdot.$

Reducing species ($H^\cdot$), hydrated electrons, and oxidizing species, ($OH^\cdot$), and H_2O_2 are generated with the following **G-values,** Spinks and Woods (1990).

$$H_2O \rightarrow [2.7]\ OH^\cdot + [2.6]\ e^-_{aq} + [0.6]\ H^\cdot + [2.6]\ H_3O^+ + [0.7]\ H_2O_2 + [0.45]\ H_2 \quad (7)$$

If we consider pure water, each 100eV of energy absorbed will generate: 2.7 radicals $\mathbf{OH^{\cdot}}$, 2.6 $\mathbf{e^{-}_{aq}}$, 0.6 radicals $\mathbf{H^{\cdot}}$, 0.45 $\mathbf{H_2}$ molecules and 0.7 molecules $\mathbf{H_2O_2}$.

$$H^{\cdot} + O_2 \rightarrow HO_2^{\cdot} \qquad (8)$$
$$HO_2^{\cdot} \rightarrow H^{+} + O_2^{-}$$

$$e^{-}_{aq} + O_2 \rightarrow O_2^{-} \,. \qquad (9)$$

Of course the presence of dissolved oxygen increases the yield of hydrogen peroxide in irradiated water by the following reaction:

$$HO_2^{\cdot} + HO_2^{\cdot} \rightarrow H_2O_2 \,. \qquad (10)$$

That is why each effluent needs to be analysed in terms of G-value when applying radiation to a real situation. The primary species $\mathbf{H^{\cdot}}$, $\mathbf{OH^{\cdot}}$, and $\mathbf{e^{-}_{aq}}$. are able to alter the organic molecules. The attack of $\mathbf{H^{\cdot}}$ (or $^{\cdot}\mathbf{OH}$) on an organic molecule (**RH**) yielding a free radical ($\mathbf{R^{\cdot}}$) and a molecule of hydrogen gas (or water) may be represented by :

$$RH + H^{\cdot} \rightarrow R^{\cdot} + H_2 \qquad (11)$$

$$R^{\cdot} + H^{\cdot} \rightarrow RH \qquad (12)$$

$$R^{\cdot} + R^{\cdot} \rightarrow RR \qquad (13)$$

$$R^{\cdot} + R^{\cdot 1} \rightarrow RR^{1} \qquad (14)$$

$$R^{\cdot} + OH^{\cdot} \rightarrow ROH \qquad (15)$$

$$R^{\cdot} + O_2 \rightarrow RO_2^{\cdot} \qquad (16)$$

Radiation Effect on Microorganisms

Radiation effects on living organisms are mainly associated with the chemical changes but are also dependent on physical and physiological factors. Dose rate, dose distribution, radiation quality are the physical parameters. The most important physiological and environmental parameters are temperature. moisture content and oxygen concentration. The action of radiation on living organisms can be divided into direct and indirect effects. Normally, the indirect effects occur as an important part of the total action of radiation on it. Radiolytic products of water are mainly formed by indirect action on water molecules yielding radicals $OH^{\cdot}$, e^{-}_{aq} and $H^{\cdot}$. The action of the hydroxyl radical (OH) must be responsible for an important part of the indirect effects. Drying or freezing of living organisms can reduce these indirect effects.

Target theory is a model which is considered to be applicable when the biological effect meets certain criteria in its relation to dose. The target theory states that the production of ionization in some particular molecule or structure (target) is responsible for the measured effect, Casarett (1968). The cells contain one or more critical sites or targets within which an ionizing event would be fatal to the cell. Genetic material, i.e. DNA, RNA, are the most important molecule in the cell, and they should be the primary target for killing the cell. The correlation of radiation sensitivity is roughly inversely proportional to size of targets. Viruses or enzymes are less sensitive to radiation treatment compared to bacterial cells . On the contrary, necessary doses for sprout inhibition of vegetables or insect disinfestation are between 20 to 500 Gy. Generally, cells in a active metabolic state are more sensitive to radiation than in a dormant or resting condition. Ito (1995).

The sensitivity of an organism to radiation is conveniently expressed as the absorbed dose required to kill 90% of the present population and the result is expressed by the D_{10} value. This decimal reduction dose is affected by irradiation conditions in which the microorganisms exist in dry or freezing, aerobic or anaerobic conditions. The D_{10} value of some organisms (responsible for selected water-born diseases) irradiated in buffer solution is presented in Table 2.

Table 2 - D_{10} Value of representing water-born-desease organisms irradiated in buffer solution

MICROORGANISM	D_{10} VALUE (kGy)	DESEASE	REFERENCE
E. coli B/r	0.34	Gastroenteritis	5
Salmonella typhimurium	0.30	Gastroenteritis	5
Mycobacterium tuberculosis	0.30	Tuberculosis	15
Shigella dysenteriae	0.60	Dysentery	15
Poliovirus (2)	1.85	Poliomielitis	32
Vibrio cholerae	0.48	Cholera	15

III. IRRADIATOR SYSTEMS

There are two different kinds of irradiators that are used for radiation processing; ^{60}Co gamma sources and electron beam accelerators. Basically the difference between gamma and electron irradiation is related to the dose rate and penetration. The penetration length of the electron beam into the material is much shorter than the penetration length of radioisotopic decay radiation having equivalent energy. With energy levels between 300keV and 10MeV, the maximum penetration depth is proportional to its energy and inversely proportional to the density of the material to be irradiated. The dose penetration can be observed by the shape of dose distribution curves for electron and gamma rays in Fig.1. Gamma rays are highly penetrating and hence enable processing of material in bulk, while energized electrons have limited penetration but can be generated at very high intensity levels from machines, which offers greater flexibility in operation. We briefly describe the most common irradiator systems.

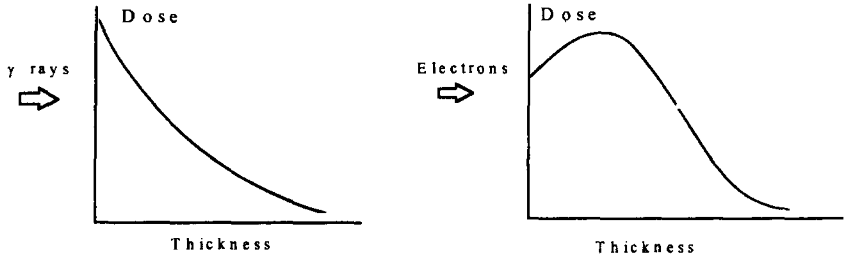

Fig. 1 - Shape of dose distribution as a function of the exposed material thickness for gamma rays and monoenergetic electrons.

The low penetration length of electrons may limit its use for processing high quantities of sewage when the treatment station belongs to metropolitan cities. However, many advances are in development in order to improve engineering systems for irradiation. Double face irradiation has been suggested and new concepts for accelerators as well. As mentioned in Sec. I, the energy is more penetrating if the electrons are used to generate Bremsstrahlung X-rays, but on the other hand, the costs may not be feasible due to the low efficiency conversion (electron to X-rays). Ballantine (1975) tried to achieve better penetration than electrons but obtained only about 6.5 percent conversion rate on electrons from a 3.0MeV accelerator. The conversion efficiency improves with increasing electron energy thereby enhancing the cost effectiveness of this treatment with higher energy accelerators.

Electron Beam Accelerator is a machine which accelerates charged particles in a single direction through electric and magnetic fields. Typically, the electrons emitted from the cathode are accelerated in a vacuum system. They then pass through a thin metal window and through the air before hitting the target. This type of machine can be classified according to the acceleration structure or, most often, according to the energy range of the electron beams. In this case, according to Yotsumoto (1995), the classification is:

- Low energy accelerator - 0.15 to 0.5MeV, 300 - 350kW. Electrons emerging from the linear cathode are accelerated in vacuum and leave the beam window without scanning. This type of accelerator is relatively small in size, since an acceleration tube is not necessary and the high voltage electrode and cathode are supported by the insulator in the vacuum chamber.
- Medium energy accelerator - 0.5 to 5.0MeV, 300 - 350kW. For medium energy accelerator, the major components are the high voltage generator, acceleration tube and its associated vacuum system, the beam processor including beam scanning system and conveyor, the control console and the safety system including radiation shielding. These components are presented in Fig. 2. The electrons are accelerated by a d-c electric field and the beam is scanned by alternating magnetic fields over the thin metal foil window. Several types of d-c machines have been developed including the Cockcroft-Walton, Dynamitron, Isolated Core Transformer.
- High energy accelerator - 5.0 to 10.0MeV, 100kW. For this type of machine the accelerating energy is transferred to thermal electrons by microwaves propagating along an accelerating tube. The microwaves are supplied by a high-power klystron operating in short pulse mode. Another alternative for accelerating methods to the microwave is the induction linear accelerator or the Rhodotron.

Gamma-Ray Source among thousands of gamma emitters only ^{137}Cs and ^{60}Co are indicated for radiation processing. The energy of gamma rays, as electromagnetic quantum waves, is similar to light, but with higher photon energy and shorter wavelength. The ^{60}Co radionuclide can be produced in a nuclear power reactor by the irradiation of ^{59}Co (metal), with fast neutrons. The radioactive isotope is formed by neutron capture as follows, Laughlin (1989):

$$^{59}Co + n \rightarrow {}^{60}Co \quad (17)$$

$$^{60}Co \rightarrow {}^{60}Ni + e^- . \quad (18)$$

The unstable nucleus of ^{60}Co emits photons of 1.17 and 1.33 MeV, decaying with a half-life of 5.2714 years to stable ^{60}Ni, Fig. 3. The radioactive ^{60}Co source is composed of small pellets of cobalt that are loaded into stainless steel or zirconium alloy sealed tubes (pencil arrays).

Ultraviolet Radiation: UV radiation for treatment of water is basically a disinfectant technology. UV is electromagnetic radiation, lying between visible and X-rays wavelengths. This kind of radiation can be artificially generated by monochromatic low pressure mercury lamps, and causes severe bactericidal action in the wavelength band lying between 200 and 310nm. The inactivation of microorganisms is essentially based upon photochemical reactions in the DNA which result in errors being introduced into the DNA. There are some limiting factors for UV disinfection of wastewater such as absorption by suspended solids, microbial initial concentration, UV absorbance, and hydraulic delivery systems. Great efforts have been made in developing suitable UV reactors.

IV. DEVELOPMENT OF IRRADIATION TECHNOLOGY IN BRAZIL

Since 1970 the inventory of wastes and studies in the required technologies carried out by *Companhia de Tecnologia e Saneamento Ambiental*, CETESB, pointed out the necessity of new alternative technologies for natural resources reutilization for São Paulo State. This study suggested

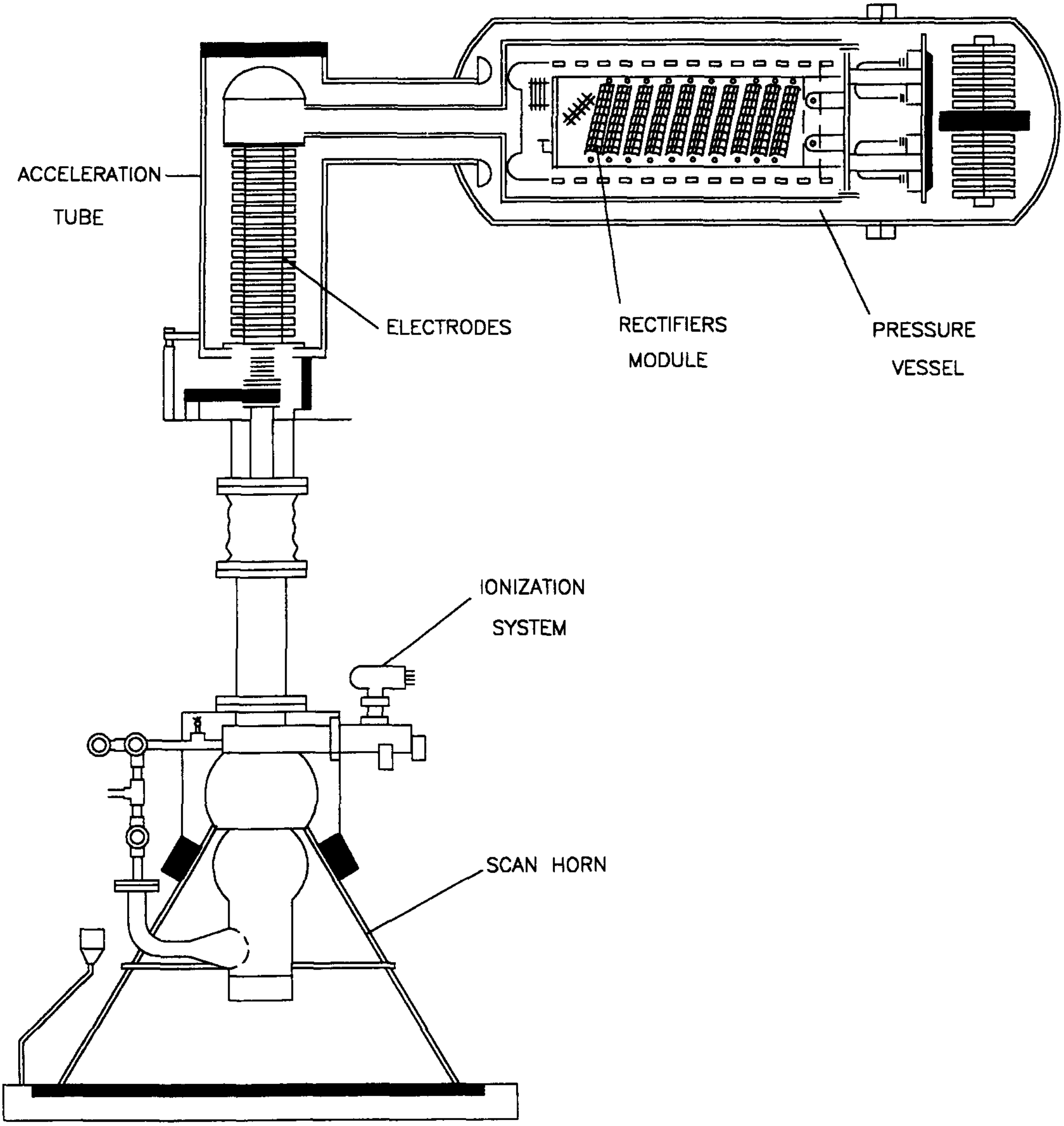

Fig. 2 - Dynamitron Accelerator (main components)

electron beam accelerators as one of the possibilities to solve this problem. Later on, Castagnet *et al.* (1982) simulated the bacterial decline using several aqueous solutions. The pH indicators were tested for simulating bacterial decay in irradiated sludge. The reduced optical density of bromothymol blue as a function of dose showed that the dosimetric response of the solution was similar to the decay of irradiated coliforms.

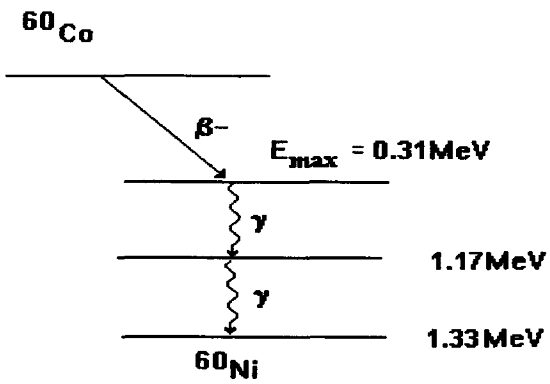

Fig. 3 - Disintegration of 60-cobalt

In 1991, the Instituto de Pesquisas Energéticas e Nucleares, IPEN (Brazil), initiated a research program based on the application of electron beam accelerators to decompose organic compounds from industrial effluents and to disinfect sewage and sludge. After obtaining promising results in batch systems, Sampa *et al.* (1992), a laboratory scale pilot plant, LSPP, was built to evaluate the feasibility of electron beam treatment for treating wastewater. Some results and the schematic diagram of LSPP are presented further.

The electron beam energy was applied to raw sewage, secondary biological sewage (secondary effluent), chlorinated wastewater and sludge, using a Dynamitron II type - 1.5 MeV, 37.5kW electron beam accelerator, from Radiation Dynamics Inc, Borrely (1995). For all experiments the irradiation was performed in batch system. The count of bacteria was made following the Standard Methods for the Examination of Water and Wastewater (1989). Required doses were obtained varying the beam current, while the energy and the conveyor velocity were kept constant at 1.4MeV and 6.72 m/min respectively. To check the absorbed dose, the free radicals produced by DL-Alanine were analyzed by Electron Spin Resonance technique.

The radiosensibility studies of pathogenic bacteria were performed using Salmonella species *in vitro*. In this case, the radiation source was a ^{60}Co gamma ray source, Yoshizawa Kiko Co, Ltd, Panoramic type, total activity 5,000 Ci.

For radiation processing of sewage, the samples were collected in a Lagoon System - Sewage Treatment Plant, composed of double lagoons classified as anaerobic and facultative. The inffluent reaches the station, passes through the collecting well, A, anaerobic lagoon, B, facultative lagoon, C, and chlorination tank, D, successively. The disinfection was observed by the elimination of indicators bacteria, total coliforms, enumerated by the Most Probable Number, MPN/100ml, through the lactose fermentation, for all studied sites. The results obtained by irradiation application are presented in Fig. 6.

Regarding sludge disinfection, the samples were collected after anaerobic digestion. The effectiveness of electron beam irradiation to residual domestic sludge, RDS, was performed by varying the thickness of the exposed layer samples (solids concentration of 16% and 30%) and the dose. The contamination was studied by the total count of bacteria, mesophilic aerobic bacteria, represented by Colony Unit Forming, CUF/ml. Results are showed in Table 3. A 10.0kGy dose reduced the total number of colonies by 3 log cycle using 1.85mm and 3.3mm of thickness. By applying a 15.0kGy dose the initial count decreased from 4.1×10^8 to a number < 10, using 1.0, 1.85, 3.3 and 4.5 mm thickness samples, Borrely and Cruz (1995).

Pilot Treatment Plant at IPEN

The purpose of the LSPP at IPEN is to perform technical and economical feasibility studies of irradiation technology when applied to real effluents remediation (industrial wastewater and sewage), *Sampa et al.* (1995).This LSPP is installed near the irradiator facility and includes the Dynamitron Electron Beam Accelerator, 1.5MeV, 37.5kW. The system consists of an irradiation device, two storage tanks (aproximately 1.2 m^3) and a hydraulic system, which allows the flow variation from 8 liters/min up to 45 liters/min, approximately. The centrifugal pumps transfer the test effluents in and out of the electron beam vault. These components can be observed in Fig. 4.

Another important component of this system is a calorimetric dosimeter which records the temperature variation as a function of the absorbed dose, through a wire current output temperature transducer (WCOTT - Intensil GE-AD590) connected to an electronic system. The data are transformed to dose by means of a special software using parameters such as liquid flow and temperature.

V. RESULTS AND DISCUSSION

After a brief overview on the ionizing radiation applied to wastewater and sludge decontamination, some results obtained with the same purpose at IPEN will be discussed.

It is certain that all cells do not respond to radiation in the same way. This affirmative points out the importance of using the same criterion of damage when comparing the radiosensitivities of different types of cells. Survival in microorganisms is defined as the ability of the irradiated organisms to multiply and form visible colonies upon incubation on some suitable growth medium.

The difference in terms of radiosensibility of the most frequent serotype of Salmonella, detected in waters from São Paulo City, Martins *et al.* (1988), can be observed in Fig. 5. *S. meleagridis* and *S. infantis* are less sensitive than *S.typhimurium*, and *S. derby*. The pattern of these curves are important as a tool for the high choice of the radiation doses to be applied to a well defined kind of effluent. The D_{10} value presents the same importance.

The effect of radiation on the elimination of indicator bacteria, i.e., total and fecal coliforms, is demonstrated in Fig. 6 which shows a 5 cycle log reduction obtained by a 3.0kGy radiation dose applied to raw sewage. The higher oxygen concentration in facultative lagoon, C, due the presence of algae, resulted in a higher efficiency of the same 3.0kGy radiation dose at that site. The final effluent, although chlorinated, was contaminated by total coliforms which were completely eliminated by irradiation.

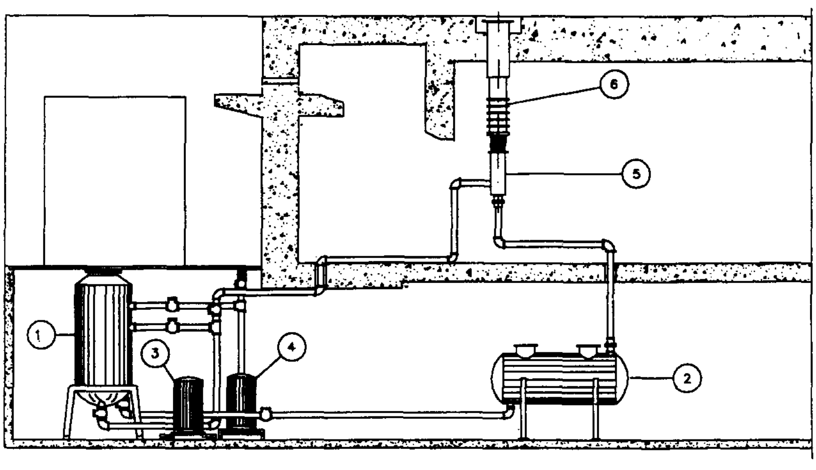

FIG.4 PILOT PLANT–SCHEMATIC DIAGRAM

1. STORAGE TANK
2. COLLETING TANK
3. HOMOGENEIZATION PUMP
4. FEED PUMP
5. IRRADIATION BOX
6. ELECTRON BEAM ACCELERATOR

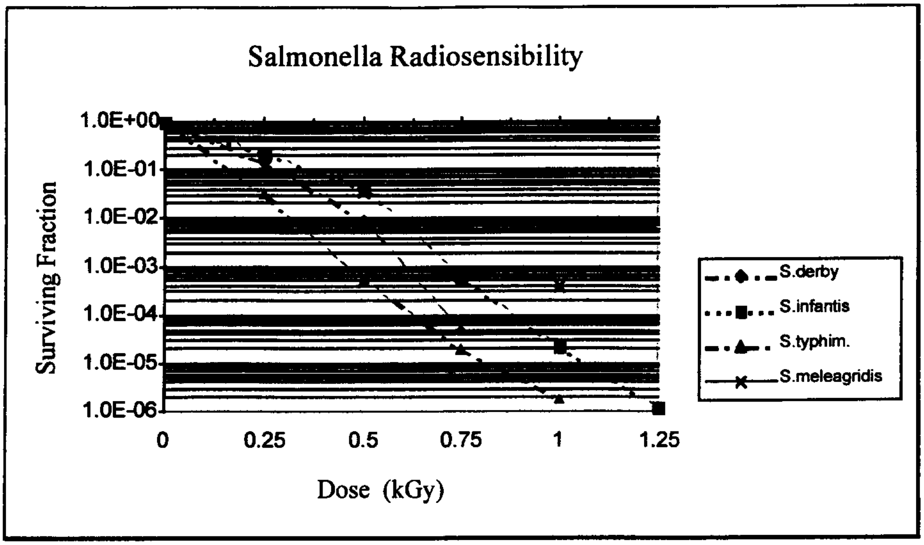

Fig. 5 - Radiosensibility of different species of Salmonella (^{60}Co)

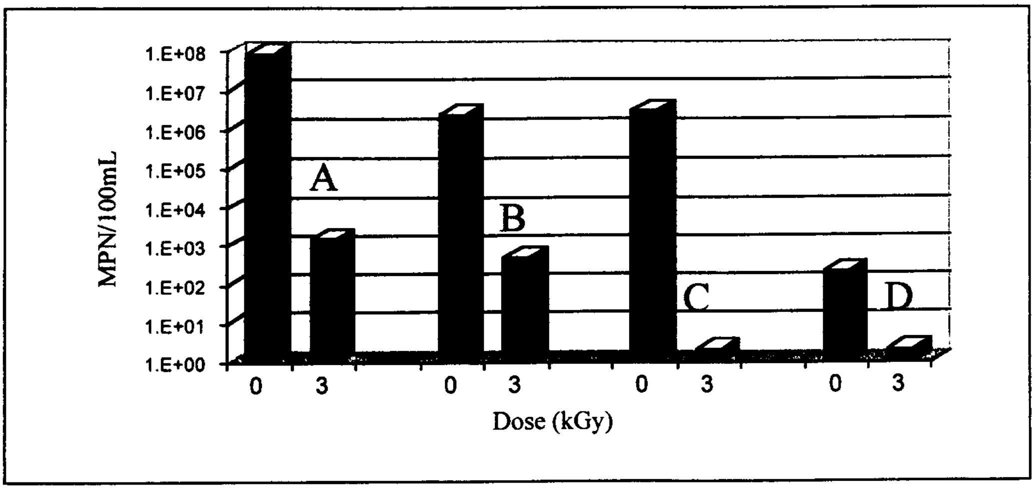

Fig. 6 - Reduction of total coliforms by 3.0kGy irradiation dose applied to Raw sewage, secondary effluent and chlorinated effluent.

The sludge disinfection required higher doses compared to sewage, as was expected. Table 3 shows a reduction of 3 cycle log and a total elimination of aerobic bacteria by 10 and 15 kGy radiation dose. Other experiments demonstrated that doses between 5.0 and 6.0kGy are enough to reduce pathogenic bacteria to an acceptable level. The level of decontamination will depend on the application of the sludge as a soil conditioner.

Table 3 -Total Aerobic Bacteria Reduction in sewage sludge by radiation dose

RESIDUAL DOMESTIC SLUDGE RDS	DOSE (kGy)	THICKNESS (mm)	TOTAL BACTERIA CUF/ml
RDS - 16.5% solids	-	-	2.6×10^9
Irradiated RDS	10.0	1.0	6.11×10^5
Irradiated RDS	10.0	1.85	5.25×10^6
Irradiated RDS	10.0	3.3	1.3×10^6
RDS - 30.12% solids	-	-	4.1×10^8
Irradiated solids	15.0	1.0	<10
Irradiated solids	15.0	1.85	<10
Irradiated solids	15.0	3.3	<10
Irradiated solids	15.0	4.5	<10

VI. CONCLUDING REMARKS

The application of radiation for the removal of contaminants plays an important role for sanitary engineering. Although gamma radiation has been used more frequently since the beginning of radiation development, we believe that electron beam accelerators are more suitable for this purpose due to versatility and lower costs. Also important is the fact that the accelerators can be turned on and off instantaneously thus facilitating control, contrary to gamma sources.

This brief review is intended to demonstrate not only the technical feasibility of this technology, but also the need of new alternative technologies. Several references have been listed to show that the electron beam energy can be useful for treating several kinds of contaminants and even for decontamination of pollutants on site.

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