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Invited Paper

SEWAGE SLUDGE IRRADIATORS
Batch and continuous flow

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Abstract

The potential threat to the environment imposed by high pathogenic organism content in municipal wastewater, especially the sludge and the world-wide growing aspirations for a cleaner, salubrious environment have made it mandatory for the sewage and sludge to undergo treatment, prior to their ultimate disposal to mother-nature. Incapabilities associated with the conventional wastewater treatments to mitigate the problem of microorganisms have made it necessary to look for other alternatives, radiation treatment being the most reliable, rapid and environmentally sustainable of them. To promote the use of radiation for the sludge hygienization, Department of Atomic Energy has endeavoured to set up an indigenous, Sludge Hygienization Research Irradiator (SHRI) in the city of Baroda. Designed for 18.5 PBq of ^{60}Co to disinfect the digested sludge, the irradiator has additional provision for treatment of effluent and raw sewage. From engineering standpoint, all the subsystems have been functioning satisfactorily since its commissioning in 1990. Prolonged studies, spanning over a period of six years, primarily focused on inactivation of microorganism revealed that 3 kGy dose of gamma radiation is adequate to make the sludge pathogen and odour- free. A dose of 1.6 kGy in raw sewage and 0.5 kGy in effluent reduced coliform counts down to the regulatory discharge limits. These observations reflect a possible cost-effective solution to the burgeoning problem of surface water pollution across the globe. In the past, sub 37 PBq ^{60}Co batch irradiators have been designed and commissioned successfully for the treatment of sludge. Characterized with low dose delivery rates they are well-suited for treating low volumes of sludge in batches. Some concepts of continuous flow ^{60}Co irradiators having larger activities, yet simple and economic in design are presented in the paper.

1. INTRODUCTION

Municipal wastewaters and sludges are potentially hazardous to the environment due to their high content of pathogenic bacteria, viruses [1], cysts and eggs of infective parasites [2] endangering human health. Degradable organic contents are also detrimental to the ecology. Indiscriminate discharging, dumping, burning and burying of these wastes has led to unacceptable levels of atmospheric pollution including the degradation and eutrophication of surface waters. Growing aspirations of mankind for a clean and healthy environment has made it necessary to return these wastes back to the nature, only with proper pretreatment. Product of wastewater treatment, the sludge is rich in plant nutrients representing an excellent, renewable source of material for soil amendment to enhance fertility. Instead of wasting such valuable resource by way of discharging, dumping or burning, its application to farmland as soil conditioner may be a acceptable alternative for ultimate disposal. Major problem associated with this, however is the possible transmission of diseases, of bacterial, viral or parasitic nature, through a man-sewage-soil-crop-man cycle [2]. Conventional wastewater treatment processes efficient as they are in stabilizing degradable organics in the sludge, are deficient in disinfecting them to acceptable levels, making one to look for other alternatives.

Several technologies exist for the disinfection of sludge. A few of them, figuring in USEPA recommendations[3], to achieve additional inactivation of micro-organisms beyond that attainable by conventional sludge stabilization methods are (1) heat pasteurization for 30 min at 70°C, (2) high pH treatment >12 by lime application for 3 h, (3) prolonged storage of digested sludge, beyond 60 d at 20°C, (4) composting at 55°C and curing in stockpiles for 30 d and (5) gamma and high energy electron irradiation under various application procedures. All these processes with the exception of radiation treatment, either have technological limitations or have problems associated with the reuse of process products. Ability of ionizing radiation to eliminate or to inactivate the microorganisms in sludge effectively, has been widely reported [4][5][6]. Albeit high in initial cost, the radiation route is simple, compact, efficient and in recent times has become more practicable due to the easy availability of large radiation sources. Radiation treatment has no adverse effect on the nutritional values of the sludge. Therefore, land application of radiation disinfected sludge, to return its organics and nutrition back to the soil is perhaps the most desirable sludge management strategy. Radiation disinfection of effluents prior to the discharge will go a long way in maintaining the quality of receiving surface waters.

2. RADIATION DISINFECTION OF SLUDGE

2.1. Radiation treatment process

Sewage sludge in liquid state (upto 8% S.S) or in dewatered state (upto 80% water content) is exposed to an intense radiation source, for a given period of time, to accumulate a specified dose which corresponds to the attaining of a desired level of microbial inactivation. Combination of irradiation with heat and oxygen [7] offers advantages in maximizing the lethality of radiation to reduce the dose requirement. A process developed in Japan [8] includes irradiation of sludge followed by composting yielded a superior, granular organic manure suitable for land application. The period of composting required for radiation treated sludge was much lower than for non irradiated sludge. Canada has developed a process where irradiation of artificially dried sludge to 25% solids is irradiated in prepackaged condition to produce organic manure named as "Bio Rich". [9]

Radiation doses generally applied for sanitizing different forms of wastewaters are,

- Effluents - Upto 0.5 kGy
- Raw sewage - 1 . 5 kGy
- Raw sludge - 3 - 4 kGy
- Digested sludge - 3 - 4 kGy
- Dewatered sludge - Upto 10 kGy

2.2. Radiation Sources

Predominant radiation sources in the Radiation Processing Industry today are ^{60}Co radioisotopes and high-energy electron accelerators. These are equally useful in wastewater applications. Use of ^{137}Cs and X-rays although promising, have yet to make a mark due to technological limitations associated with these sources. The use of UV in wastewater application is on the rise[7], the technique working at its best on water devoid of particulate matter. Cobalt-60 decays at an annual rate of 12.5% continuously and periodic source replenishment is essential for maintaining the throughput constant. This feature however is not attributable to high energy electron from accelerators.

2.3. Sludge irradiation systems

Sludge irradiation systems (sludge irradiators) are built as an add-on facility to the conventional wastewater treatment plant, for the sole purpose of disinfection. Liquid sludge irradiators can be designed to operate in batch or in continuous flow mode with the use of pumps and piping. Irradiation of dewatered or dry sludge is carried out in irradiators identical to those used in medical product sterilization equipped with unit package conveyor system.

3. BATCH IRRADIATORS

The batch irradiators for sludge built so far, are designed for ^{60}Co having source capacities below 37 PBq. These irradiators are inherently low dose rate units and are well-suited for the treatment of sludge low in volume and intermittently drawn from the conventional plant. A batch of measured volume of sludge is drawn in batches in a vessel charged with radiation source and is recirculated in radiation zone within the vessel, by a high flow capacity pump. Recirculation homogenizes the sludge within radiation zone for uniform irradiation throughout its volume and prevents settling of suspended particles which tend to block narrow passages in the system. Period of recirculation of sludge in radiation zone depends on the source strength, lower source strength requiring longer period of recirculation. At the end of recirculation period, sludge is evacuated from irradiation vessel and is despatched for land application. This process is then repeated for the next batch of sludge. The entire operation can be automated to minimize the human dependance.

A biological shield is provided around the irradiation vessel for the protection of operating staff. Source requirement of a batch irradiator is dictated by factors, such as, volume of sludge to be treated per day and source to water geometry signifying the efficiency of radiation utilization. The rheological properties of sludge and degree of mixing required in the irradiation zone influence selection of mechanical equipment like pumps.

3.1 Examples of batch irradiators

3.1.1. Sewage sludge irradiator, Geiselbullach, Germany [10]

The first technical scale plant for disinfection of sewage sludge by Gamma-radiation was built in 1973 at Gieselbullach, near Munich, Germany. The project was jointly supported by Federal and Bavarian Agricultural and Scientific Institutes and equipment manufacturers. A combination of ^{60}Co and ^{137}Cs sources was tried successfully in the plant. Salient features of the plant are

- Nature of sludge - Anaerobically digested liquid sludge (< 5% SS)
- Max source design capacity - 25 PBq, ^{60}Co
- Max processing capacity - 180 m^3/d at 3 kGy
- Volume per batch - 6m^3
- Source geometry - Cylindrical

A cylindrical irradiation vessel with radiation sources mounted on its hollow central pipe in a cylindrical source geometry is housed in an underground shaft. A concrete plug covering the shaft provides for the radiation protection. Source transfer in vessel is carried out underwater by flooding the irradiation shaft. Recirculation and evacuation pumps are housed in another underground shaft, 4 m away. The sludge is recirculated from inner to outer annulus of the vessel partitioned by the source holder. After radiation disinfection, the liquid sludge is transported by tankers for spreading on the farmland.

Unfortunately, for the past couple of years, the plant is out of operation due to some technical reasons. The consistency in attaining inactivation of microorganisms and the nutritional benefits to the crops, accruable from radiation treated, recycled sludge have been extensively studied and the success of the process has been amply demonstrated in this generic plant.

3.1.2. Sewage sludge irradiation project, PIBA, Argentina [11]

A new ^{60}Co based sludge irradiator at Tucuman, Argentina has design features similar to Geiselbullach irradiator. The project is funded by Argentina's National Economy Funds through National Atomic Energy Commission. IAEA is supporting the part of research work through Coordinated Research Programme.

Main features of the plant are

- Sludge characteristics - Anaerobically digested, liquid sludge (8 - 10% SS)
- Max source activity - 26 PBq of ^{60}Co
- Max processing capacity - 180 m^3/d at 3 kGy
- Volume per batch - 6m^3
- Source Geometry - Cylindrical

Following the irradiation, sludge is drained out of irradiation vessel, under gravity to an outlet tank. Source transfer operation is carried out by flooding irradiation shaft and source transfer shaft with demineralised water. Radiation sources are continuously cooled with the help of demineralized water, which in turn is cooled in a heat exchanger. Provision for oxy-irradiation also features in the plant design.

3.1.3. Sludge Hygienization Research Irradiator (SHRI), Baroda, India

To demonstrate the role that radiation technology can play in the preservation of environment, the Department of Atomic Energy set up SHRI facility, integrated with an existing 22 MLd, conventional sewage treatment plant in Baroda.

The main features of the plant are,

- Sludge characteristics	- Anaerobically digested (4% SS)
- Maximum source capacity	- 18.5 PBq
- Maximum processing capacity	- 110 m^3/d at 4 kGy
- Volume per batch	- 3 m^3
- Source geometry	- Planar grid source

Irradiator system consists of two independent radiation chambers, built above ground level, each having a separate, stainless steel, rectangular irradiation vessel of 3 m^3 volume. One of the chamber, at any given time is under operation while the other is serving as a standby. Radiation sources are installed in the vessel in planar grid geometry. Sludge, while entering in the vessel falls perpendicular to the source plane and flows towards the outlet through large gaps provided in the source grid. Source assembly consists of a planar frame of 13 tubes of 42 mm ID X 48 mm OD to accommodate 26 nos. of integral source units of 38 mm OD X 693 mm length. Source transfer in the vessel is carried out remotely, with the use of a special transport container and its accessories. The components of source transfer system e.g. source container, rails, source loading ports and grid tubes in the irradiation vessel are carefully aligned during construction. A mechanical key interlock system (castle locks) ensures that from the thirteen loading ports only one port, aligned and shielded by the source container is opened at a time. Inside the vessel sources are cooled by a separate cooling water system which also provides for the monitoring of sources for leakages, if any.

Entry to the radiation chamber is through a maze. access to the active cell is totally prohibited with the help of key interlocks and by welding of maze entry door with the doorframe. Sludge feed and recirculating system consists of s.s. piping and cast iron pump with s.s. open impeller. Plant controls and safety systems include control of irradiation period, monitoring of the flow and levels of sludge, radiation monitoring and ventilation of radiation chamber. Microbiological, physical and dosimetry investigations are carried out in house. Various systems of SHRI facility are shown in Fig. 1.

3.1.4. Operational experience at SHRI

3.1.4.1. Microbiological aspects [12]

Since its commissioning in 1990, with an initial charge of 5.5 PBq of ^{60}Co, the plant is continuously in operation. Research efforts so far have been primarily focused on the study of microorganism response to radiation. Effects of irradiation from pathogen reduction standpoint on primary effluent, secondary effluent, raw sewage, raw and digested sludge have been investigated routinely. Results of these studies are briefly summarized in Fig. 2 to Fig. 4, indicating that, a dose of 0.5 kGy brings down the coliform counts in effluent water below regulatory discharge level of 100/mL. A dose of 1.5 kGy is adequate to sanitize raw sewage from its very high initial counts to an acceptable level and a dose of 3 kGy is sufficient to sanitize raw as well as digested sludge for safe reuse. Significance of these indices lies in revealing the fact that effluent water and raw sewage can be sanitized at much lower doses than the concentrated sludge. The technology could therefore offer a realistic solution to serious issue like cleaning of river waters, which are highly polluted and save them from further pollution caused by the cities on the banks. Big rivers like Ganga receive large volumes of wastewater, often untreated, from the cities dotted on her banks. Coliform counts as high as 10^6 to 10^7 MPN/100 mL have been reported [13] at some locations indicating severe bacterial contamination in the water. Story is the same for other rivers as well. Ministry of Environment and Forests has shown a keen interest in this technology to clean the water of Ganga, in a massive "Clean Ganga" campaign.

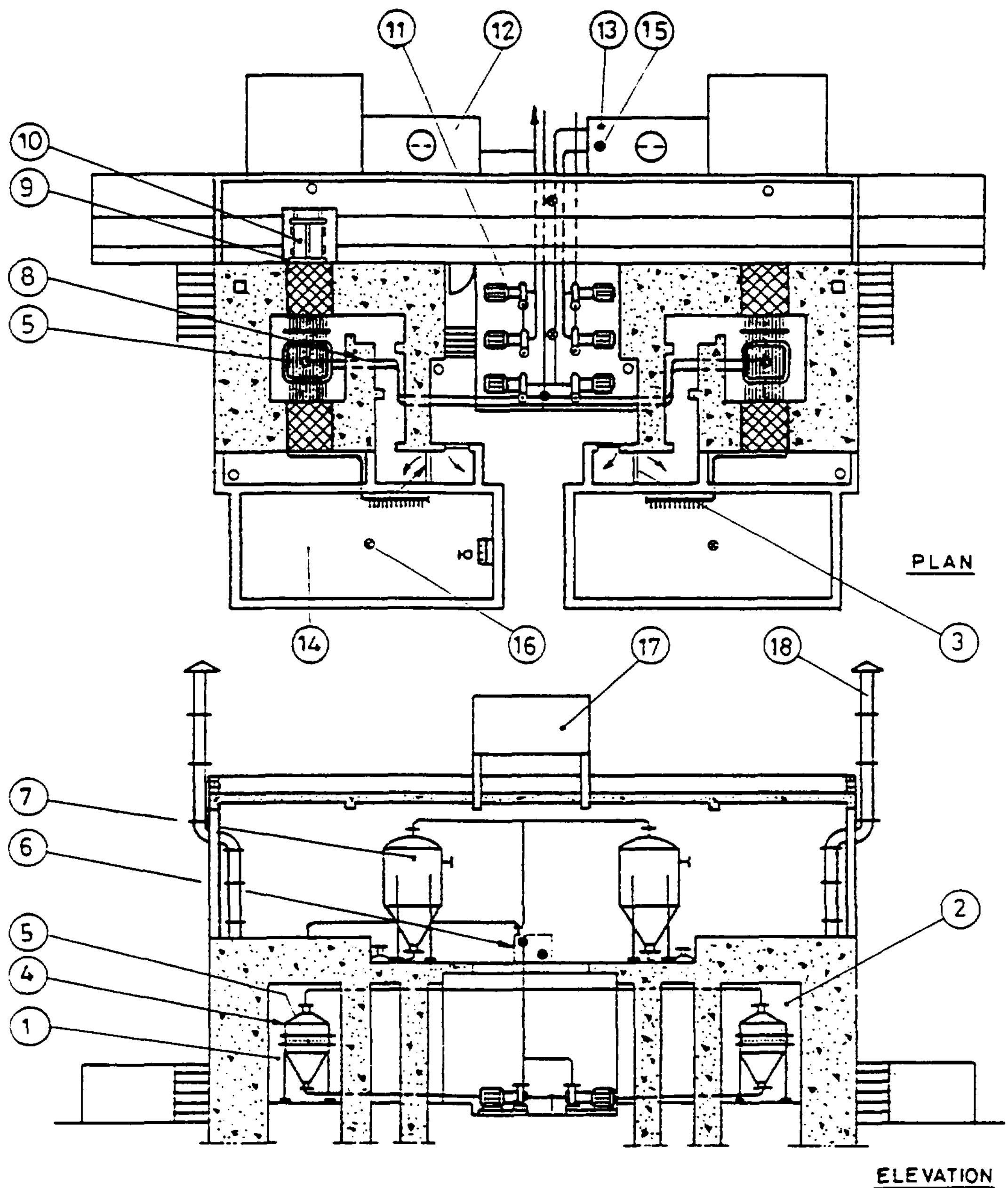

FIG. 1. The SHRI irradiator system, Baroda, India (1: irradiation cell with maze access; 2: alternate cell for source storage and development; 3: sealed maze access with double door protection; 4: irradiation vessel; 5: source assembly; 6: source coolant system; 7: silo storage; 8: recirculation piping for sludge; 9: source loading and unloading arrangements; 10: radiation source transfer and transport container; 11: pump house; 12: inlet reservoir (sludge); 13: outlet reservoir (sludge); 14: control room; 15: contamination monitoring and control systems; 16: fire protection systems; 17: water reservoir with water level monitors; 18: obnoxious gas exhaust).

3.1.4.2. Engineering aspects

All plant-engineering systems have been performing very well during this period. Minor modifications in recirculation and feed loop were incorporated to prevent formation of dead pockets, to reduce static head requirements and to prevent choking of pipes at the restrictions. During the processing of raw sludge additional screening of the sludge was found desirable to remove long , fibrous materials present in it. Source loading and unloading operation, carried out several times so far, is performed with ease and safety proving reliability of interlocks provided in the plant.

3.1.4.3. Dosimetry aspects

In initial phase of the plant operation, a nylon film encased in a PVC ball that circulated with the sludge in radiation zone was used as a routine dosimeter in the plant. This method was found to be inconvenient for following reasons,

- Movement of the balls and sludge being unidentical led to variations in the results.
- Density difference between the nylon film and the sludge.
- Problems associated with the retrieval of balls from the system.

A new dosimetry technique based on thermoluminisance of sand particles present in irradiated sludge was developed in SHRI [14]. The dose vs TL response of 370°C TL peak in H_2O_2 treated sand samples was found to be linear within 1 to 5 kGy, a dose range that covers most of the wastewater applications. This method is found to be highly reproducible and is now used for routine dosimetry of the irradiated sludge.

3.1.4.4. Coordinated research programme

Department of Atomic Energy is actively participating in two separate Coordinated research programme under research contract from the joint FAO/IAEA Division by using facilities at SHRI.

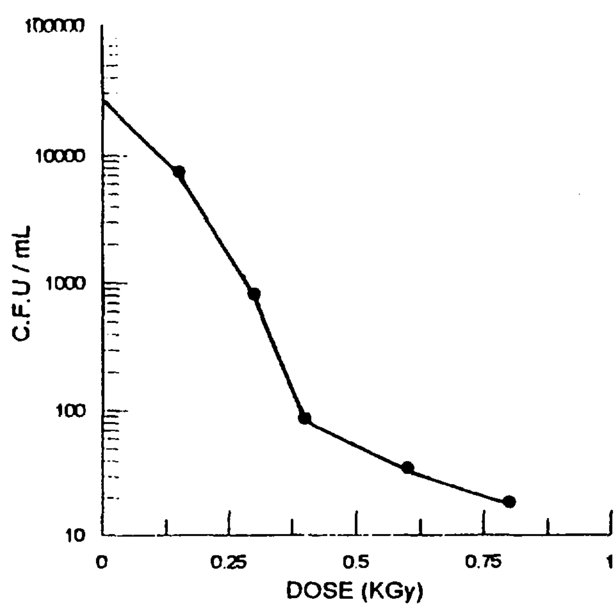

FIG. 2. Survival curve for coliforms in primary effluent.

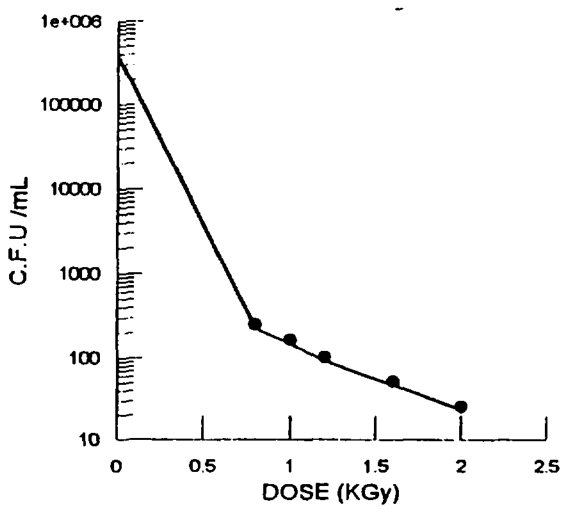

FIG. 3. Survival curve for coliforms in raw sewage.

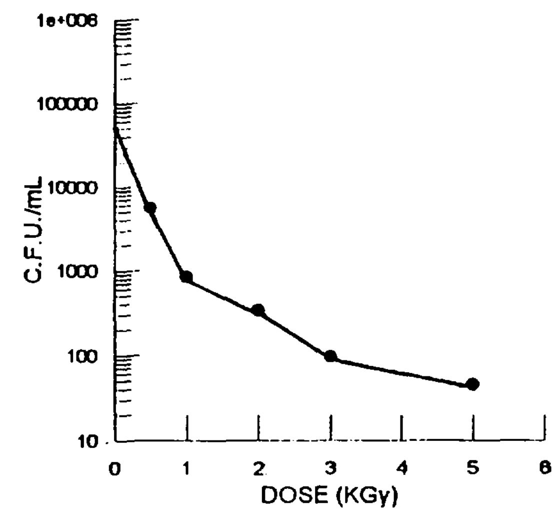

FIG. 4. Survival curve for coliforms in sludge.

The first CRP titled "The use of irradiated sewage sludge to increase soil fertility, crop yields and to preserve the environment" [16] is being pursued at Nuclear Agriculture Divison of BARC, Trombay. Initial results indicate that the soil conditioning attributes of irradiated sludge like crop productivity, pH, electrical conductivity, uptake of phosphorous and heavy metals were in no way inferior to those of non-irradiated sludge. The second CRP titled "Radiation hygienization of raw sewage sludge" is being pursued at SHRI. Studies on the response of microorganisms in raw sewage to radiation at varying doses are being conducted.

4. CONTINUOUS FLOW IRRADIATORS

4.1. High energy electron accelerators

Continuous flow irradiators developed for wastewater application so far, use high energy electron accelerators as a source of radiation. These machines are inherently suited for continuous treatment of wastes, in liquid form or dewatered, dried and prepackaged form of appropriate thickness under the beam of accelerated electrons at a steady rate. For a given radiation dose, gamma radiation emitted by ^{60}Co source or a beam of high energy electrons generated in an accelerator has same lethal effects on microorganisms. Difference, however lies in their range of penetration in the material under treatment. Radiation emitted by ^{60}Co can penetrate much deeper in the sludge in comparison to high energy beam electrons. A medium power electron accelerator of 50 kW is equivalent in processing capacity to a 127 PBq ^{60}Co irradiator which by any standard is a pretty large, radioisotope source. Accelerator technology is constantly advancing and very compact, high powered, high efficiency machines capable of processing very large quantities of wastewater are now readily available. The processing rates are easily controlled and maintained by adjusting the beam current in the machine. Unlike radioisotope sources, which continuously emit radiation, electron accelerator can be switched off whenever desired. Appropriate method of presentation of sludge to the beam in very thin layers has to be devised. While ^{60}Co irradiator is reasonably simple to operate, electron accelerator due to its sophisticated electronic and electrical systems demands highly experienced staff for its maintenance and operation.

4.1.1. Examples of continuous flow irradiators

4.1.1.1. Deer Island Electron Research Facility, Boston, USA [16]

The facility equipped with 850 keV, 50 kW electron accelerator was commissioned in 1976 integrated with Boston's largest wastewater treatment plant at Deer Island. Built with US National Science funding, the facility played a key role in the elaborate, scientific studies carried out by Massachusetts Institute of Technology, USA in collaboration with other institutions on the biological, chemical, engineering and economic feasibility of disinfecting liquid municipal sludge by treatment with energized electrons. Sludge (5% SS) was presented to the electron beam in a continuous flow, in the form of 1.2 m long and 2 mm thick film generated by a drum-roll technique. Processing capacity of the plant was 0.4 MLd at a dose of 4 kGy. Different sludge presentation techniques were tried for performance evaluation for future applications.

4.1.1.2. The Virginia Key waste water treatment plant, Miami, USA [7]

A 75 kW, 1.5 MeV electron accelerator built by Miami Dade Water and Sewer Authorities with support of USEPA is operating at Miami, USA since 1988 for the research work on disinfection of drinking water, wastewater and destruction of chemicals in wastewater. A curtain of water, 2 to 5 mm in thickness, continuously falling over a weir is presented to the electron beam for irradiation. The Unit is designed to provide a dose of 4 kGy to 0.6 MLd of sludge per day.

4.2. Continuous flow ^{60}Co irradiators

Cobalt-60 irradiator can be designed to operate in a continuous flow mode. Advantage of a continuous flow irradiator over a batch irradiator is that the time lost in evacuating and filling of irradiation vessel during batch change operation is saved, resulting in a better utilization of the radiation energy. To allow for a specified period of residence to sludge in radiation zone, the sludge flow rate needs to be controlled accurately. Velocity of sludge in this case is much lower as compared to the velocity of recirculating sludge in batch irradiator, leading to absence of turbulence in the vessel. A large variation in the spatial of dose rate distribution also exists in irradiation vessel. For these reasons a thorough agitation of sludge in radiation zone, either with mechanical means or with pressurized air, is essential for maintaining uniformity in administered dose to the sludge. Source requirement of an irradiator depends on the magnitude of the dose to be delivered and the volume of sludge to be processed per hour.

4.2.1. Continuous flow ^{60}Co irradiator with cylindrical source

A conceptual design of continuous flow irradiator is shown in Fig. 5. Irradiation vessel of circular cross section, similar to that of a batch irradiator is placed in a water pool of appropriate depth, water providing the biological protection. Vessel has a cylindrical source

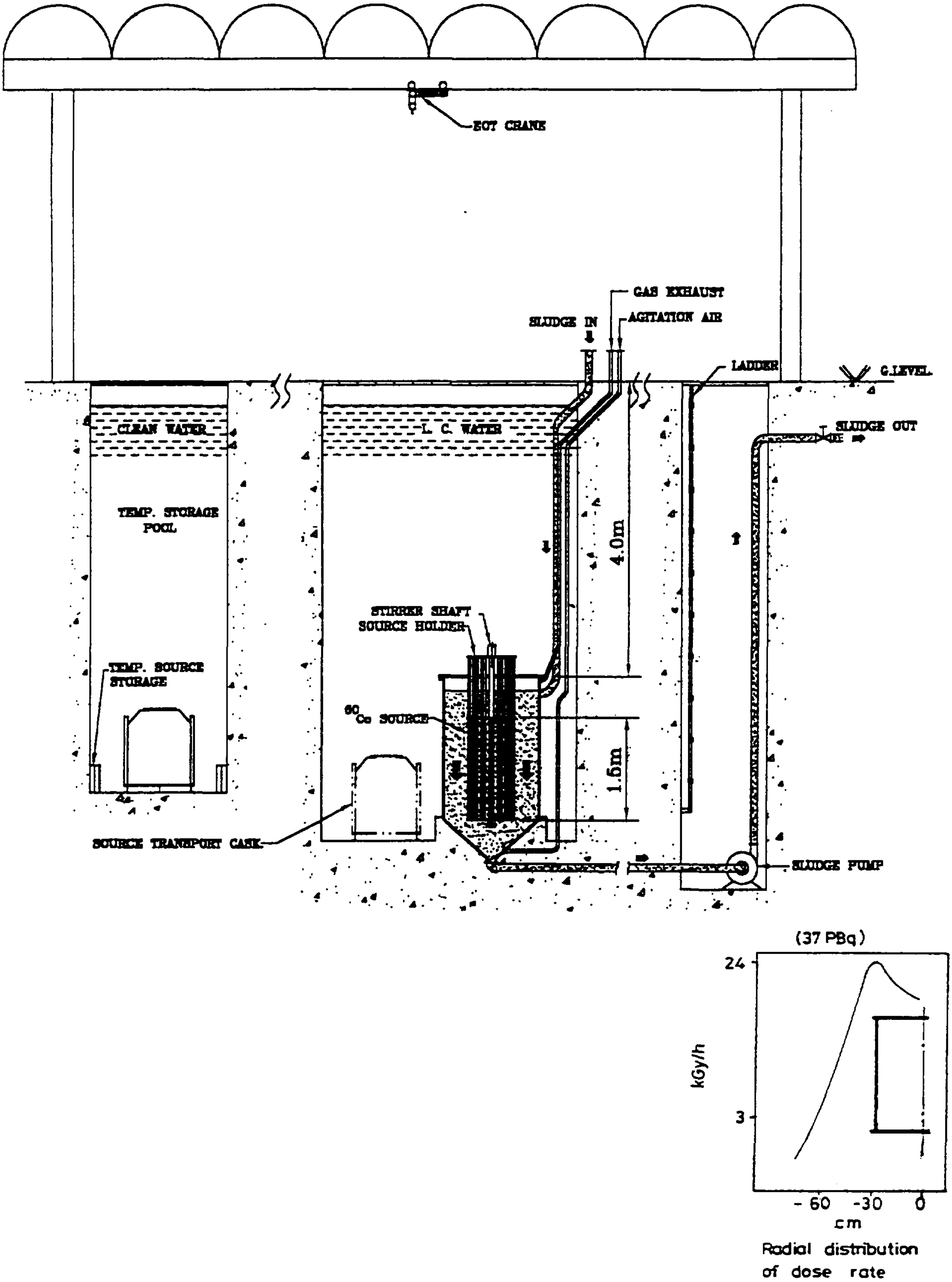

FIG. 5. Continuous flow sludge irradiator, cylindrical source (concept).

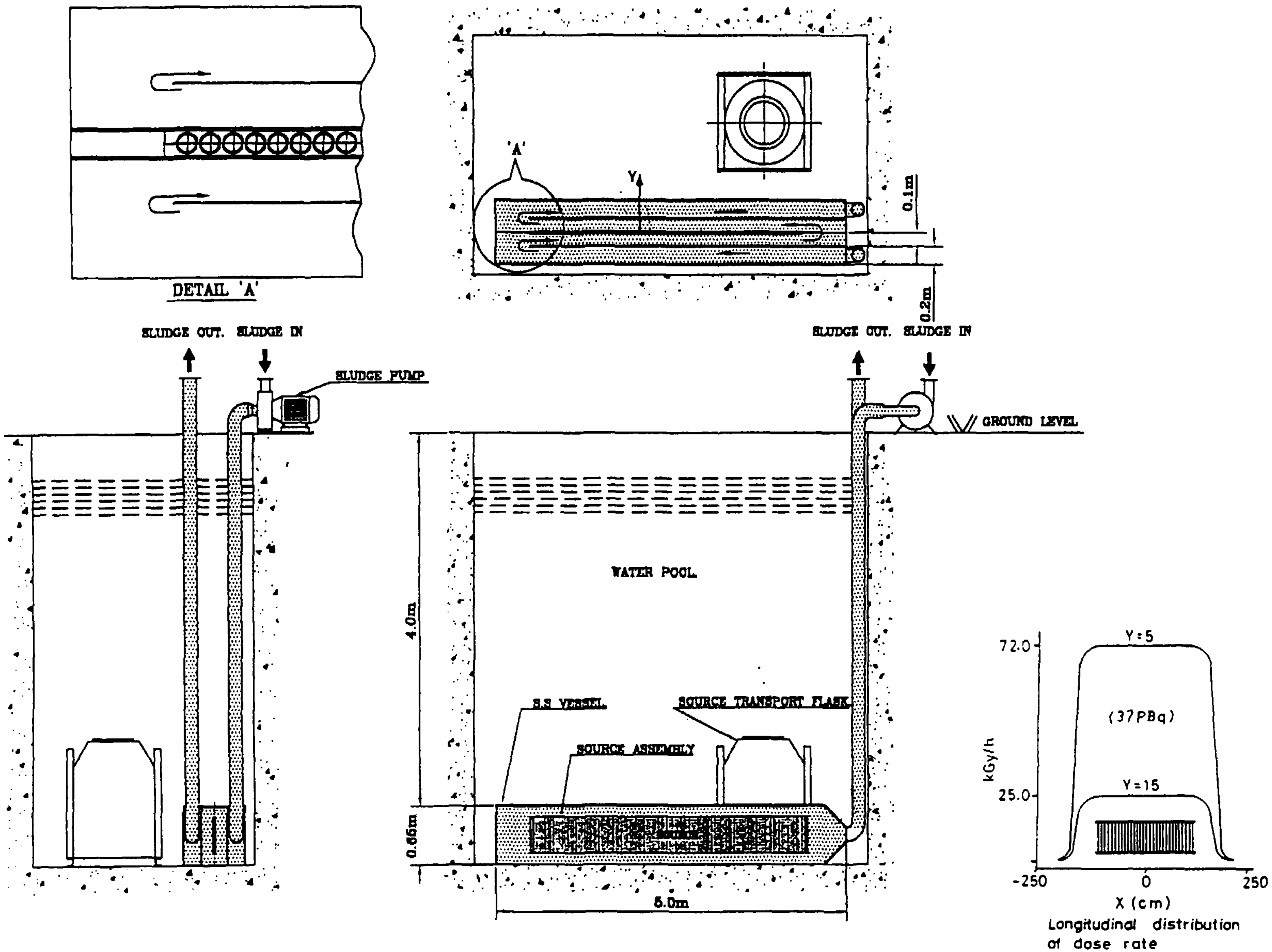

FIG. 6. Continuous flow sludge irradiator, slab type source (concept).

cage, its tubular source channels projecting out of the vessel to open in pool water. This provides a safe and easy access to the sources during source transfer operation shortening the maintenance period. Pool water is always kept isolated from the sludge. Sludge admitted at the top of the vessel descends slowly downwards, at a fixed rate, to provide adequate residence time for the sludge in the radiation zone. Vertical gaps provided between the two adjacent source channels allow free flow of agitated sludge throughout the volume for uniform irradiation. Sludge flow rate is controlled by pump capacity control or by throttling of the discharge valve. Increase in velocity of sludge at the exit of vessel will discourage the particles to settle in downstream flow passages. Provision of an additional water pool adjacent to the main pool to function as a temporarily source storage enhances the flexibility in plant maintenance. Other components not shown in the schematic include, screens, feed pump, flushing water connections, stirrer, level gauging and control system etc. A provision to recirculate initial charge of sludge at the start up is desirable.

Preliminary calculations carried out by using Sievert integral method indicate that for 37 PBq of ^{60}Co, distributed in a source holder of 0.6 m in diameter and 1.5 m high, each layer of sludge will reside in the irradiation zone for about 8 min to accumulate a dose of 4 kGy, which corresponds to a processing rate of 10 m^3/h.

4.2.2. Continuous flow ^{60}Co irradiator with planar (slab) source

Another conceptual design of a continuous ^{60}Co irradiator is shown in Fig. 6. In this case a planar source (slab source) integral to the irradiation vessel with rectangular flow passages is used. The vessel is placed at the bottom of a water pool, water being used as a radiation shield. Fluid enters the vessel at one end and makes four passes past the radiation source before leaving the vessel. To prevent settling of particles in the vessel high fluid velocity is essential and for this reason the available residence time, in this case, is rather limited. This design is well suited for processing large quantities of wastes having lower solids content at relatively lower radiation doses, such as, effluent and raw sewage. From the preliminary calculation, using Sievert integral method, it is estimated that for about 37 PBq of ^{60}Co, approximately 80 m^3/h of effluent at a dose of 0.5 kGy can be processed in such irradiator.

5. CONCLUSIONS

Radiation treatment of wastewaters and sludges has the potential of being a single, largest application of radiation of nuclear as well as machine origin. The technology is far superior to the rival technologies and facilities to meet specific applications can be built. Although not yet cost competitive, reduction in the capital and operational cost is expected by bringing in some standardization in the design and manufacture of such facilities. Only then the process will become attractive and acceptable to municipal authorities, the potential users of this technology.

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