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DISINFECTION OF MUNICIPAL SLUDGE AND WASTEWATER BY ENERGIZED ELECTRONS.

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Abstract

Laboratory studies at M.I.T. and high flow rate studies at the M.D.C. Deer Island Wastewater Treatment Plant in Boston have shown the practicality and cost effectiveness of disinfecting liquid municipal sludges by injecting energized electrons.

A dosage of 400 kilorads (4 kilograys) reduces gram-negative bacteria, including coliforms, fecal coliforms, salmonellae and shigellae, in primary raw or anaerobically digested sludges to undetectable levels. Enteric viruses are reduced by one to two orders of magnitude. This treatment also destroys parasite eggs or renders them non-infectious. Model system studies indicate that trace toxic compounds such as PCBs in water are degraded.

The estimated cost of sludge disinfection by electron treatment is about $0.80 per liquid tonne for modular systems of 650 liquid tonnes per day capacity. About 6 kilowatt-hours of input electric power per tonne is required. The temperature rise of the disinfected watery sludge is about 2° C.

Electron disinfection combined with subsurface soil injection offers an environmentally attractive, energy-efficient, and economic two-step process for land disposal of municipal sludges with water conservation and soil improvement benefits. Combined with widely-distributed ocean feeding, electron disinfection of the municipal sludge of coastal communities offers a safe marine nutrient for increasing fish population in treated ocean areas. The electron disinfection of effluent wastewater, in lieu of chlorination, is a future application which avoids the production of potentially toxic chlorinated hydrocarbons.

Energized Electrons and Environmental Needs

Public health concern over the disposal of municipal sludges on land and the discharge of chlorinated wastewater into rivers and coastal waters has stimulated efforts to use ionizing radiations to achieve more thorough disinfection.[1] Penetrating electrons energized by machine accelerators[2] and gamma rays from radioactive isotopes[3] distribute their powerful disinfecting action throughout the volume of contaminated liquids without the production of potentially toxic chlorinated compounds. The ionizing energy needed for sludge disinfection raises its temperature less than 2° C and achieves far more complete control of pathogens than can be accomplished by conventional biological digestion.

Among potential bacterial pathogens, salmonellae, shigellae fecal streptococci and fecal coliforms cause the most concern. In Switzerland, Hess (1975) found that neither aerobic stabilization nor anaerobic digestion significantly reduced salmonellae and showed that these pathogens can survive for more than a year in sewage sludge spread on grass.[4] Along coastal waters of many countries, shellfish harvesting has been banned because of their accumulation of human enteric viruses, shellfish toxins or certain industrial chemical compounds.

The recycling of sewage sludge on land as a valuable resource can also be compromised by risk of parasital infection.[5] Man is the definitive host of the pork tapeworm _Taenia solium_ and the beef tapeworm _Taenia saginata_. In recent years, the incidence of _T. saginata_ has increased in many countries, notably in Germany and Poland.[6] In the United States, _Entamoeba histolytica_ and _Ascaris lumbricoides_ are regarded as the more serious parasites. Large numbers of _Ascaris_ ova are released in the feces of infected man or animal and can survive 7 years in soil. In some populated areas of South Africa, the _Ascaris_ ova content of digested and waste activated sludge averages 3,000 eggs per gram dry weight.

Energized electrons are the most available and economic form of ionizing energy for the treatment of liquid wastes. Electron beam power can be applied to the destruction of pathogenic bacteria, viruses and parasites in liquid municipal sludges, in the septage from unsewered communities, and in the wastewaters from large animal farms. The subsequent application of these disinfected materials on land, preferably by the environmentally attractive subsurface injection method, yields useful water conservation, soil conditioning and plant fertilizer benefits.

Electron beam power is not limited by availability to the treatment of municipal sludges. For inland population centers, electron treatment could replace chlorination for the disinfection of effluent municipal wastewaters. This would avoid the progressive contamination of the drinking waster of downstream communities with potentially toxic chlorinated hydrocarbons. There is evidence that electron treatment tends to destroy trace amounts of polychlorinated biphenyls and similar persistent toxic chemicals which may already be present in water solution.[7]

For large population centers bordering on oceans and with poor access to land - New York, Boston, Rio de Janeiro - electron disinfection can be combined with widespread ocean distribution. Disposal of disinfected municipal sludge by ocean feeding would provide a safe nutrient for the phytoplankton and algae level of the fish food pyramid.[8] Its ultimate effect would be to increase the fish population in the treated ocean areas.

In the United States, passage of the 1972 Water Pollution Control Act was a recognition of the worldwide and growing pollution of the streams, lakes and coastal waters of the earth. Two international conferences on the peaceful uses of atomic energy had encouraged the effort to utilize ionizing radiations for better sludge and wastewater management. In March 1975, an IAEA conference in Munich, hosted by the Bavarian Provincial Institute for Agriculture and Plant Culture, was attended by 150 participants representing 24 nations.

At the Sandia Laboratories in Albuquerque, in cooperation with the New Mexico State University, the feasibility of sludge disinfection by gamma rays from the fission waste product Cesium 137 came under investigation with U.S. government support in 1974. Sludge disinfection studies using energized electrons became an active program in the Boston region at about the same time.

Electron Disinfection Studies at M.I.T. and Deer Island.

In May 1974, a research team supported by the National Science Foundation with participants from the Massachusetts Institute of Technology (MIT), the University of New Hampshire (UNH), the University of Massachusetts (U Mass.), and the High Voltage Engineering Corporation (HVE) began an evaluation of the biological, engineering, and economic feasibility of liquid municipal sludge disinfection by the injection of high energy electrons. An important practical aspect of this study was the setting up at Deer Island, Boston's largest wastewater treatment plant operated by the Metropolitan District Commission, of an electron research facility capable of disinfecting liquid primary sludge at the rate of 70 GPM. This treatment rate is equivalent to 100,000 GPD, or one-third of Deer Island's daily sludge flow.

The extensive microbiological and engineering studies which followed have confirmed that raw and digested primary sludges, waste-activated primary and secondary sludges, and composted sludge can be effectively and economically disinfected by an approppropriate dosage of energized electrons. The bacteriological studies were performed at MIT both on pure cultures and on raw and anaerobically digested Deer Island primary sludges. The virus inactivation studies were carried out at UNH after irradiation at MIT or Deer Island.

These studies indicate that 400 kilorads (4 kilograys) is an adequate dosage for liquid sludge disinfection.[9] At this dosage, the total bacterial count is reduced by 4 to 5 orders of magnitude, and total coliforms, salmonellae and shigellae are reduced to essentially non-detectable levels.[10] A few eggs of Ascaris, probably the most resistant parasite, may still embryonate at 400 kilorads but their ability to infect has been destroyed.[6]

Table 1 lists the bacterial counts measured in Deer Island primary raw and anaerobically digested sludge. Primary raw sludge is seen to contain over 10^8 bacteria per ml. About half of the total bacteria are in the gram-negative category which includes the bacterial pathogens, salmonellae and shigellae. It can be observed that anaerobic digestion reduces the various bacterial counts by only 1 to 2 orders of magnitude.

Figure 1 shows the survival curves for total bacteria, total coliforms and salmonellae in raw primary sludge as a function of the electron dosage. It is notable that coliforms and salmonellae diminish rapidly and nearly exponentially with dosage; their counts are reduced by 8 orders of magnitude (logs_{10}) at 250 kilorads. The total bacterial counts include the more resistant gram-positive sporulating bacteria and therefore diminish slowly after the sensitive bacteria are destroyed.

The effects of electron treatment on fecal coliforms in primary raw and anaerobically digested sludge is shown in Figure 2. Violet red bile agar was used at elevated temperature for quantifying fecal coliforms in sludge samples. The D_{10} value (the electron dose which causes a 10-fold reduction in surviving organisms) in both primary raw and digested sludge is 28 kilorads; there is no detectable survival of fecal coliforms over 300 kilorads dose.

At Deer Island, the dosage was recorded as the total electron beam current in milliamps (ma) incident on the full sludge width of 120 centimeters. For correlation purposes, the minimum dose can be taken as 70 kilorads for each 10 ma of beam current.

Figure 3 shows electron inactivation of total coliforms and gram-negative bacteria in primary anaerobically digested sludge irradiated at the Deer Island Research Facility. The total bacterial count is reduced by about 4 orders of magnitude at 40 ma electron exposure. In case of coliforms and gram-negative bacteria, about 5 to 6 logs reduction takes place at 20-30 ma electron exposure.

Figure 4 is representative of the many pure culture survival-dose studies made on specific organisms during the project period. Each curve shows the characteristic response of that specific organism to electron treatment. This response to a physical agent - the ionizing electrons - is relatively less influenced by factors such as solids content, presence of toxic chemicals, pH and nutrition which can critically upset biological processes.

Table 2 lists the characteristic responses of bacteria to electron treatment as determined in pure culture studies in terms of the D_{10} dose.

Table 3 lists the D_{10} dose for various bacterial groups in primary raw and digested sludges, and in secondary waste-activated sludge.

Virus Inactivation by Energized Electrons.

The viruses of public health concern are primarily of human origin. In domestic sewage, the enteric virus population rises to a peak in late summer and declines to less than one-tenth their concentration in the cold months.

Though all enteric viruses can produce clinical symptoms, the infectious hepatitis virus is by far the most serious. Since it is almost impossible to culture and quantitate this virus in laboratory, five other enteric viruses were used as stand-ins in the MIT-UNH studies.

Virus inactivation work was carried out by Professor T. G. Metcalf and his co-workers at University of New Hampshire supported by National Science Foundation and coordinated with the M.I.T. project.[11] The virus samples and the sludge samples containing test virus were treated with electrons either at M.I.T. or at the Deer Island research facility. Metcalf found that up to 95% of the virus content of influent wastewater at Deer Island is removed in primary raw sludge. Thickened raw sludge with 4% solids contained from 100 to 1000 viruses per gram at peak. Anaerobic digestion generally reduces the virus concentrations of raw sludge by 2 to 3 orders of magnitude.

Energized electron disinfection of viruses has generally been considered the result of irreparable damage to viral nucleic acid structures. This study showed that a nearly two-fold increase in electron dose is required when viruses are suspended in wastewater sludge as compared to wastewater effluent.

Virus inactivation studies using poliovirus 2 in primary anaerobically digested sludge indicate that a 1 to 2 log reduction is obtained by electron treatment with a dosage of 400 kilorads. This reduction in virus content is adequate for anaerobically digested sludges but possibly marginal for primary raw sludges at the late summer peak of virus input. Electron effectiveness was not influenced by the type of enterovirus used in the study. coxsackievirus B3, echovirus 7 and poliovirus 2 inactivation rates were relatively similar in comparable experimental conditions.

The ability to destroy human enteric virus pathogens by electron treatment of municipal sludge and wastewater offers a non-polluting energy-saving method of reducing virus-caused public health concerns associated with these liquid wastes.

Degradation of Toxic Chemicals in Wastewater and Sludge.

As part of the MIT-NSF studies, the effect of energized electrons on trace toxic chemicals, such as polychlorinated biphenyls in pure water solution, was investigated. These studies, by Dr. E. W. Merrill and his students in MIT's department of chemical engineering, were extended to trace toxic chemicals in model systems consisting of water with increasing percentages of lipid analogous materials.[7]

Analyses by reverse-gradient high pressure liquid chromatography (HPLC) showed that, in pure water, trace quantities of several PCBs are destroyed by doses of 1 to 10 kilorads. The HPLC technique disclosed that the residual molecular fragments were more water-soluble than the parent compound. At 50 to 100 kilorads, the neighboring degradation fragments have also disappeared. This evidence suggests that attack by the hydroxyl radicals produced by dissociation of water is the principal mode of degradation.

The effectiveness of this degradation process is progressively inhibited with increase in the lipid content of the watery medium. In pure hexane, an electron dose of 5 megarad produced only a 90%degradation. Several models simulating the lipid concentration found in municipal sludges (0.1 to 0.5%) showed substantial degradation of PCBs at the 400 kilorad disinfection dose.

This preliminary experimental data suggests that the substitution of electron disinfection for chlorination of effluent wastewater would avoid the direct production of chlorinated hydrocarbons and might also significantly reduce trace toxic compounds of the PCB type which may already be present.

It appears economically feasible, and it is clearly technically feasible, to replace chlorination of effluent wastewaters from municipal treatment plants which discharge into streams and rivers (figure 12).

Liquid sludge represents a far more complicated case because of the protection against hydroxyl radical attack afforded by the lipid content. In wastewater treatment plants, the lipid-soluble toxic compounds in sludge are likely to be concentrated in the floating grease and scum and therefore relatively immune to electron degradation. It is desirable that the grease and scum of wastewater treatment plants be skimmed and incinerated as is the practice in many European installations. Subsequent disinfection with electron dosage of 400 kilorads might then destroy the remaining water-dissolved PCBs and other toxic organic compounds.[13] Further direct experiment to demonstrate this is planned.

Electron Beam Power.

Electrons are the most useful and most available of the basic electrified particles of nature. First identified in 1897 as exceedingly small, negatively-charged particles by the English physicist J. J. Thomson, the physical properties of electrons and their fundamental role in the structure of atoms and molecules are now well understood. Electrons are recognized as the beneficent particle of nature, the energy carriers essential to electric power transmission and conversion, long-distance communications, industrial controllers, computer systems, and medical diagnostic devices.

When accelerated in an evacuated tube to high energies by the action of an electric field, electrons become a very special form of electric energy. One million volts, so applied, causes electrons to move with 94% of the speed of light. At such energies, electrons can be passed from vacuum through a thin sheet of metal into air and penetrate into solid and liquid matter. Their task of ionizing the target material is typically completed within one billionth of a second after emission from their heated filament source.

The penetration of energized electrons into matter is much less than that of X-rays and gamma rays of equivalent energy. The maximum range for 1 million volt electrons is about 4 meters in air or about 5 mm. in water. At higher voltages, the electron penetration increases proportionately. In transit through matter, whether solid, liquid, or gaseous, each electron loses energy by random collisions which excite and ionize thousands of atoms and molecules along its track.

The distribution of ionization in depth of unit density material, such as water or sludge, produced by monoenergetic electron beams of several energies is shown in Figure 5. The region of maximum ionization density occurs at an intermediate depth because of the pronounced scattering of these exceedingly light particles.

The ionizing power P in kilowatts in a directed stream of such energized electrons is equal to the product of the accelerating voltage V in megavolts and the electron beam current in milliamps. The energy absorbed in passing through the thin metal 'window' is typically about 5% at 1 megavolt. The moving target material should be arranged so that the emergent electrons will penetrate and ionize it throughout the volume.

The past two decades have witnessed the development of electron accelerators with the penetrating ionizing capacity and on-line reliability required for industrial processing. Over 2 megawatts of energized electron power is now installed for a variety of full-time industrial applications. Electron accelerators with output beam powers from 25 to 150 kilowatts are commercially available in the voltage range from 0.3 to 3 megavolts. The choice of output power and voltage depends on the volume, thickness, density and required dosage of the material to be treated.

For wastewater and sludge disinfection, it is significant that 100 kilowatts of electron beam power is equivalent to the total gamma ray emission of 7 million curies of Cobalt 60, or to over 25 million curies of Cesium 137. Yet electron beam power can be turned on and off at will and does not induce radioactivity at the voltages needed for large-scale disinfection.

The bar chart of Figure 6 shows radiation effects versus dosage in rads from the small doses used in diagnostic radiology, through the tumoricidal doses needed in cancer therapy, to the pasteurization and sterilizing doses of interest in the wastewater and sludge applications.

Deer Island Electron Research Facility.

This investigative system at the MDC Wastewater Treatment Plant in Boston was built for realistic engineering and disinfection efficacy studies on liquid municipal sludges. Designed as an in-line system for flow rates up to 70 GPM, corresponding to 100,000 GPD, the electron beam power utilized a 50-kilowatt, 850-kilovolt electron accelerator with electron beam scanner supplied by the High Voltage Engineering Corporation. The facility became operational in April, 1976.

At Deer Island, the liquid sludge was presented as a wide thin layer moving in a single pass through a downward-directed scanning electron beam. Disinfection requires that all of the contaminated sludge receive an adequate ionizing dosage. Thus the full width and thickness of the moving sludge layer must be effectively penetrated by the electron beam. The reliable control of the fluid sludge layer and its coordination with the energized electron source was a central purpose of the study.

The maximum penetration into liquid sludge of 850 kilovolt electrons is about 4 mm. and the effective disinfection range for electron injection from one side is about 0.6 of this value. Recognizing the inevitability of thickness variations, an average sludge thickness of 2 mm. was chosen in planning the 100,000 GPD throughput of the experimental facility. This provided some margin before occasional excessive thicknesses could result in inadequately treated material. The moving sludge layer was 1.2 m. wide, averaged 2 mm. thick, and flowed through the scanning electron beam at nearly 2 m. per second.

The physical studies at Deer Island are now substantially completed. They have shown decisively that the necessary coordination of sludge thickness with electron penetration could be achieved at this sub-megavoltage level. Pretreatment of the sludge by grinding is necessary for raw sludge and desirable for digested sludge to produce a uniformly smooth liquid slurry. It was found that the simplest and best performance could be obtained with a downward-directed sludge layer exposed to a horizontally-directed electron beam. It was recommended that a higher electron voltage would further facilitate the operation.

The entire electron injection and sludge disinfection operation takes place within a thick-walled concrete enclosure which absorbs the x-rays inevitably produced by the deceleration of energetic electrons. The shielding is designed so that no significant x-radiation escapes to the outside.

Electron disinfection has the operational advantages that the system can be started or fully deactivated in seconds and is inherently suited to automatic control. Dosage is controlled by regulating the electron beam current. At electron voltages below 1.67 MV, no radioactivity can be induced in any material subject to the electron treatment.

Figure 6 shows an aerial view of Deer Island with an arrow indicating the electron disinfection research facility. The MDC Deer Island Wastewater

Treatment Plant, in operation since 1969, receives over 300 million gallons per average dry day and serves the population of part of Boston and 43 outlying communities. About 300,000 gallons per day of anaerobically digested sludge is released with the chlorinated effluent wastewater into Boston harbor at times of outgoing tide.

Figure 8 is a diagram of the in-line electron treatment system. Operated at intervals for research and engineering purposes, its disinfection capacity is one-third of Deer Island's daily sludge production.

Figure 9 is a sketch of the concrete shield surrounding the output end of the 50KW electron accelerator at Deer Island.

Figure 10 shows the drum-roll method of applying energized electrons to a wide thin layer of sludge moving at constant speed through the ionizing beam. This was the first of six methods investigated at Deer Island for presenting a uniformly thin sludge layer to the electron beam.

Sludge Disinfection at Miami.

In Miami, Florida, the Miami Dade Water and Sewer Authority is proceeding with plans for testing a 170,000 gallon per day electron system for the disinfection of their anaerobically-digested and waste-activated liquid sludges. Several similar paralleled electron treatment modular systems would have the capacity and redundancy to treat the total 1985 Miami sludge throughput (600,000 gallons or 645 m^3 per day).

The single-modular demonstration system will adopt the recommendations of the Deer Island study. The penetration of the energized electrons will be nearly doubled by increasing the voltage from 850 to 1500 kilovolts. The scanned electron beam will be horizontally projected toward a downwardmoving layer of liquid sludge. The electron beam power will be 75 kilowatts. This system is planned for completion late in 1980.

Figure 11 shows a proposed lay-out and shielding arrangement for the Miami demonstration system.

Sludge Disinfection Costs.

The estimates of capital and operating costs of municipal sludge disinfection are based on Deer Island experience and the following assumptions: 1) That the annual disinfection time is 83% of the total hours in a year. 2) That the disinfection dosage is 400,000 rads. 3) That the annual capital recovery is 10% of the capital cost. 4) That electric power is 3.5 cents/kwhr.

Four sizes of accelerator systems are indicated. The 50 kw system approximate that at the Deer Island facility. The 75 kw system is similar to that planned for the sludge of the city of Miami. Calculation of the annual sludge throughput is illustrated in the next section.

Electron Beam Power in kilowatts[1]	Electron Voltage	Annual Disinfected Sludge with 83% Operating Time		Annual Capital Cost[2]	Annual Costs[4]
		gallons in millions	Wet tonnes	in $1000s[3]	
25	1 Mv	15	57,000	350	90
50	1 Mv	30	114,000	500	120
75	1.5 Mv	49	186,000	685	159
100	2.0 Mv	69	262,000	825	193

1. Larger annual volumes are managed by paralleling two or more identical modules for redundancy and cost saving. Modular units with 200 kw of output electron beam power can be designed and built if needed.

2. Total capital cost includes electron accelerator system and sludge handling

equipment, excluding housing.

3. 1978 dollars.

4. Annual costs include electric power at 3.5 cents/kwhr., operation and maintenance, and capital recovery over 20 years.

Annual Sludge Throughput vs. Electron Beam Power.

Assumptions are:

a) the least disinfection dosage is 400 kilorads.
b) the electron utilization efficiency (EUE) = 35% for 1 Mev electrons, 38% for 1.5 Mev electrons, and 40% for 2 Mev electrons. One Mev refers to the energy of an electron accelerated by 1 million volts.
c) electron injection is from one side.
d) the system operates at full capacity for 83% of the year.

The disinfected liquid sludge throughput for 50 kw electron beam system operating at 1 million volts is calculated below. The throughput equals

$$50 \text{ kw} \times \frac{10^3 \text{ joules}}{\text{sec kw}} \times 10^7 \frac{\text{ergs}}{\text{joule}} \times \frac{400 \text{ krad dose}}{4 \times 10 \ \frac{\text{ergs}}{\text{gram}}} \times \frac{1 \text{ lb}}{454 \text{ grams}} \times \frac{1 \text{ gal}}{8.35 \text{ lbs.}} \times 0.35$$

= 1.155 gallons per second (GPS)

=30 million gallons per 7270 hour year (83%)

= 126,000 wet tons per 83% year

= 115,000 wet tonnes per 83% year

The annual throughput for 75 kw and 100 kw systems can be extrapolated from this calculation by adjusting the electron beam power and correcting for the improved electron utilization efficiency obtainable at higher voltages.

Thus, annual throughputs for 75 kw and 100 kw are about:

49 million gallons	or	205,000 wet tons
69 million gallons	or	288,000 wet tons

Energy and Cost Per Liquid Tonne

The energy needed for sludge disinfection by electrons is very low in comparison to thermal disinfection. A rad is defined as the absorption of 100 ergs per gram; 400 kilorads would therefore raise the temperature of water or watery sludge just 1°C. In actual systems, the temperature rise after passing through the electron beam is about 2° C because much of the sludge receives more than the 400 kilorad 'least' dose treatment.

About 6 kw-hrs of input AC power is required per tonne of liquid waste disinfected to the 400 kilorad level.

The cost per liquid tonne to disinfect sludge using a 100 kilowatt modular electron system is estimated to be about 80 cents for a 400 kilorad dose. This estimate includes capital recovery cost over 20 years, electric power, supervision and maintenance expenses. Such a system could disinfect 260,000 liquid tonnes per year. Four such modular systems, operating in parallel, could disinfect the total sludge of greater Boston and provide the desirable system redundancy. Costs for lower treatment doses are proportionately lower.

Preliminary evidence indicates that the disinfection of influent or effluent wastewater from municipal treatment plants can be accomplished with an electron dose of 100 kilorads or less. This lower dose (compared to the 400 kilorads for sludge), coupled with the higher electron utilization efficiency obtainable with opposing-sided injection into the effluent layer, could bring the disinfection cost per liquid tonne close to that of sodium hypochlorite disinfection. Elimination of the public health concerns and costs introduced by chlorinated hydrocarbons would be the valuable environmental benefit. Figure 12 illustrates the opposing-sided injection method.

Land Application of Electron Disinfected Sludge.

Electron disinfection combined with direct soil injection can safely and attractively apply liquid municipal sludges and septage to the land for their soil improvement benefits. These two management steps eliminate the need for chemical treatment and dewatering. They avoid bulky composting materials and procedures. The process relies on electron treatment for the destruction of pathogenic organisms and on the physical and biological activities of earth to stabilize the well-distributed sludge solids and convert them into fertile soil.

Professor J. L. Smith and his associates at the Department of Agriculture Engineering at Colorado State University, assisted by an NSF/RANN grant, have developed a rapid subsurface injection method which is now in use at a dozen communities in the United States.[12] The sludge is implanted 4 to 6 inches below the soil surface as it is lifted momentarily by a tractor-drawn rig with multiple cultivator sweeps of special design. The liquid is deposited below the surface, mixed with the soil, and covered in one continuous process.

The 1977 USEPA guidelines encourage subsurface injection as the most acceptable method of sludge application:

> "Techniques for applying liquid sludge include: tank truck, plowing, injection, or ridge and furrow spreading . . . . The use of <u>incorporation and injection</u> is encouraged as a means of improving public acceptance by decreasing possible odor generation and

unsightly deposits on crops."

Equipment for the Colorado State University method is produced by Briscoe Maphis, Inc. of Boulder, Colorado which also supplies services for site selection, application rate determination, operator training, and subsequent soil and ground water monitoring as required under the EPA's land application guidelines.

In this land application procedure, liquid sludge of up to 7% solids is delivered to the tractor-drawn injector through a long flexible butyl rubber irrigation hose which is connected to a piped pumping system. This in turn is connected to the sludge storage facility. The injection operation looks like a farmer plowing his field (Figure11). Usually one can walk across the injected soil within minutes.

Subsurface injection essentially eliminates odor problems and speeds up the conversion of sludge into soil. Although generally applied to digested sludges, it is equally applicable to unthickened raw sludge. The liquid sludge can be injected at rates up to 35,000 gallons per hour. Depending on local soil characteristics and climate, injection can be repeated on sites intended primarily for disposal every 2 to 4 days. Subsurface injection remains physically feasible until the ground is frozen to a depth greater than 3 inches but may become unadvisable for reasons of impaired nitrification and denitrification when the soil temperature at the 12-inch depth drops below 4°C . Closed tanks and lagooning are the preferred methods of storage of the liquid sludge for the winter months.

Ocean Feeding of Electron Disinfected Sludges.

The electron treatment which can eliminate major public health concerns in the application of municipal sludge to agricultural land also makes possible the beneficial utilization of such treated sludges as an ocean nutrient. Many coastal cities of the United States and other countries, among them Boston, New York, London, Tokyo, Rio de Janeiro, have inadequate access to sufficient agricultural land to utilize the resource values of their municipal sludges.

For such coastal cities, the economic and environmentally attractive two-step process of nutrient feeding ocean areas is recommended. These steps consist of (1) thoroughly disinfecting the liquid sludge by electron treatment, and (2) repeated feeding of this disinfected liquid material over extensive ocean areas from tank barges towed to selected regions to promote the growth of algae and other fish food plant forms.

Electron disinfection of liquid municipal sludges is accomplished by a compact and efficient automated treatment process which has low energy requirement and causes no atmospheric contamination. Towing the electron-disinfected sludge to selected ocean regions likewise involves low energy consumption. Barge transport is acknowledged as the most reliable and most cost-effective year-round transportation method. The sludge is released as a watery slurry from the barge as it is towed over an extended course so as to properly distribute its nutrient values. This spreading operation also contributes to the rapid dilution of any heavy metal content in the sludge to levels close to those already naturally present in ocean waters.

Electron disinfection followed by widespread ocean feeding eliminates several conventional sludge management steps with their high capital and operation costs, high energy consumption and adverse environmental impacts. For example, compared to Boston's interim plan to incinerate the sludge of greater Boston at the MDC Deer Island Treatment Plant, this new ocean feeding alternative would eliminate:

(1) the addition of chemicals to promote dewatering;
(2) physical dewatering by rotating machinery or filter presses;
(3) incineration;
(4) ash removal and disposal;
(5) atmospheric pollution by incinerator gases;
(6) adverse esthetic effects on neighboring communities.

Compared to New York City's proposal to compost its sludges in floating enclosed systems, this new electron disinfection and ocean feeding alternative would eliminate:

(1) addition of chemicals to promote dewatering;
(2) the energy-consuming dewatering operation;
(3) the capital and operating costs of floating composting systems;
(4) the risk of polluting the city's air with pathogenic organisms including the spores of <u>Aspergillus fumigatus</u>;
(5) distribution of composted sludge to many city-controlled land sites;
(6) monitoring such application sites for groundwater, surface and air contamination.

In February 1979, the High Voltage Engineering Corporation submitted a proposal to Boston's MDC and to EPA's Office of Water and Hazardous Material which included an offer to supply a complete electron disinfection/ocean distribution system for Boston sludge. This same "solution" is applicable and available for the sludge problems of other coastal cities. Marine biologists have agreed that the electron disinfection/ocean feeding process would not 'unreasonably degrade the marine environment.' It would be in compliance with international public law and would contribute valuable nutrient to the hungry ocean and thereby increase the ocean supply of fish.

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High Voltage Engineering Corporation of Burlington, Massachusetts, supplied by lease to MIT the 50-kilowatt electron accelerator for the Deer Island facility with full maintenance. The services in microbiology by D. N. Shah and in system operation by B. deBree were supplied by HVE at cost along with substantial technical assistance without compensation.

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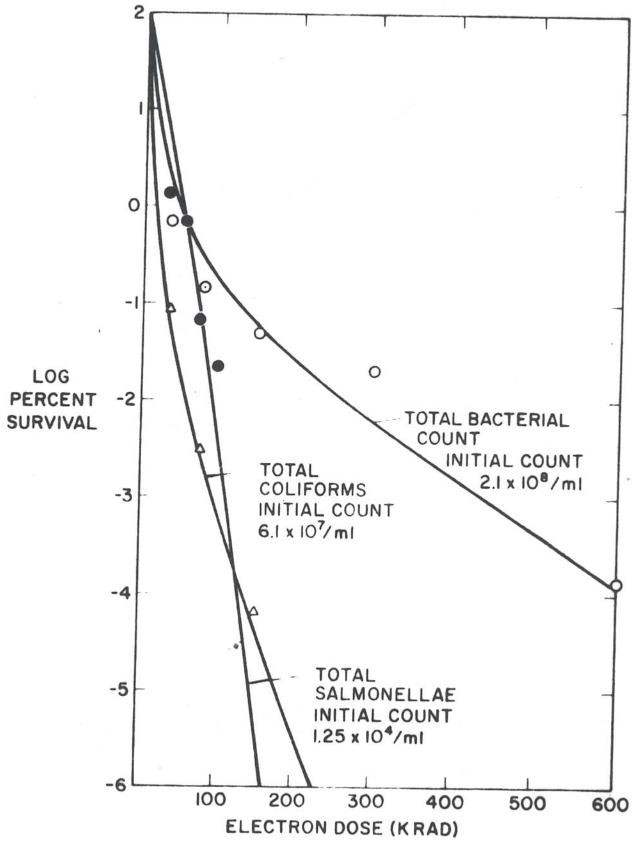

Figure 1. Electron Inactivation of Bacteria in Primary Raw Sludge

TABLE I

NUMBERS OF BACTERIA IN DEER ISLAND WASTEWATER RESIDUALS

BACTERIA	MEDIA*	RAW PRIMARY SLUDGE	ANAEROBICALLY DIGESTED SLUDGE
Total bacteria (aerobic and facultative)	a	2×10^{8}/ml	4×10^{6}/ml
Total coliforms	b	7×10^{7}/ml	8×10^{5}/ml
Fecal coliforms	c	2×10^{6}/ml	1×10^{5}/ml
Gram-negative bacteria	d	1×10^{8}/ml	1×10^{6}/ml
Clostridia	e	2×10^{5}/ml	6×10^{4}/ml**
Salmonellae	f	1×10^{4}/ml	4×10^{1}/ ml
Fecal streptococci	g	5×10^{4}/ml	5×10^{3}/ml
Anaerobic bacteria	h	3×10^{6}/ml	2×10^{5}/ml

*NUTRIENT MEDIA USED IN THE ASSAY PROCEDURES

a. Trypticase soy yeast extract agar, incubation temp. 30°C

b. MacConkey's agar - lactose fermenting colonies, incubation temp. 37°C

c. Violet red bile agar, incubation temp. 45.5°C

d. MacConkey's agar - lactose fermenting and non-fermenting colonies, incubation temp. 37°C

e. SPS agar, incubation temp. 37°C

f. Bismuth sulfite agar, incubation temp. 37°C

g. KF Streptococcus agar, incubation temp. 35°C

h. Trypticase soy yeast extract agar, incubation temp. 37°C

** TSN agar, incubation temp. 37°C

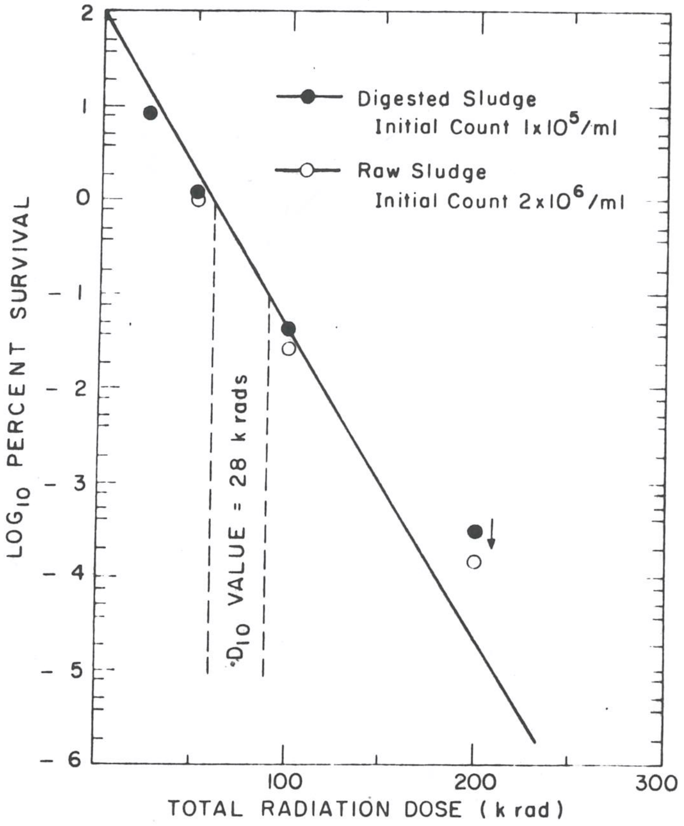

Figure 2. Electron Inactivation of Fecal Coliforms in Primary Raw and Anaerobically Digested Sludge

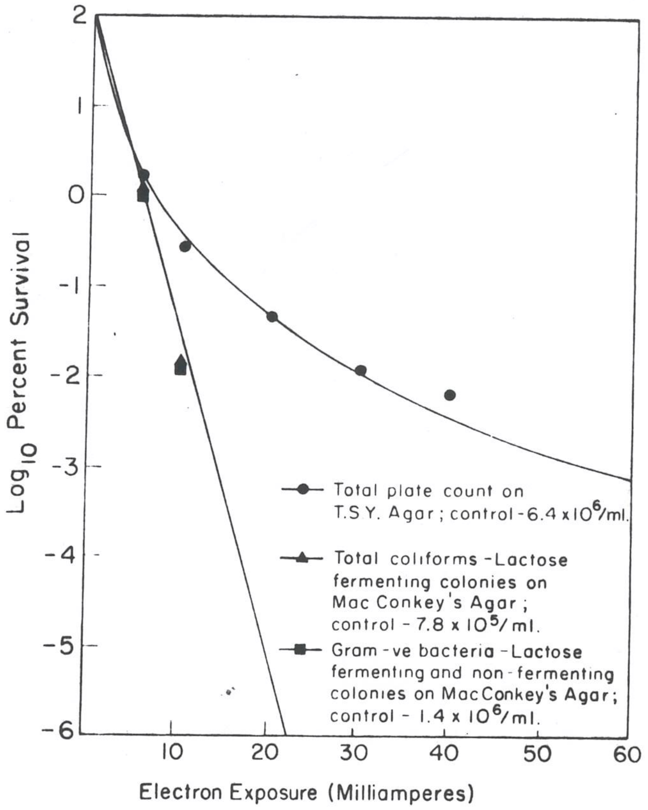

Figure 3. Inactivation of Coliforms and Gram-Negative Bacteria in Primary Anaerobically Digested Sludge Electron-Irradiated at the Deer Island Research Facility

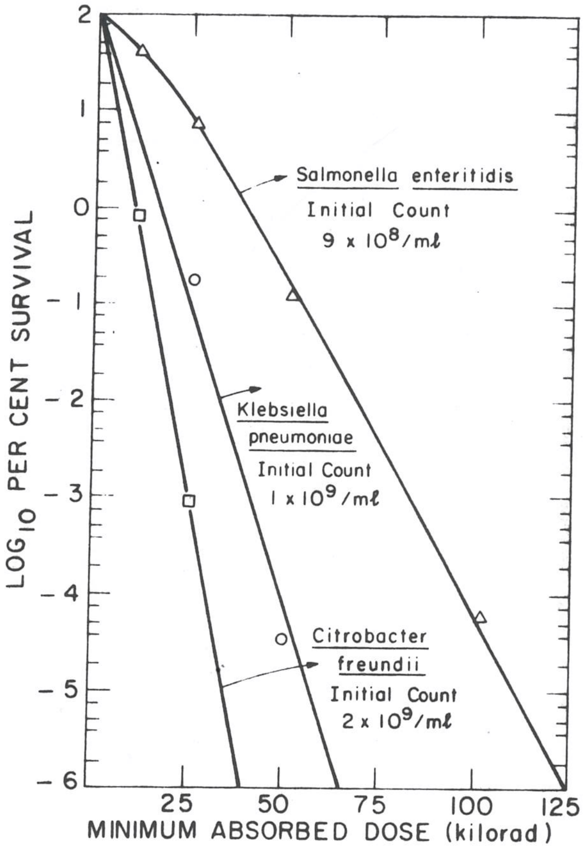

Figure 4. Effects of Electron Irradiation on Salmonella enteritidis, Klebsiella pneumonia and Citrobacter freundi

TABLE II

D_{10} (90 Percent) Inactivation Electron Dose for Various Microorganisms in Pure Cultures

	D_{10} Dose (Kilorads)	Calculated Log_{10} Reduction for 400 kilorad Electron Dose
Escherichia coli strain K12	27	15.0
Micrococcus species	14	28.0
Citrobacter freundii	5	80.0
Klebsiella pneumoniae	12	33.3
Salmonella enteritidis	15	26.6
Salmonella typhimurium strain LT2	16	25.0
Salmonella typhimurium strain R6008	105	3.8
Salmonella typhimurium strain 24	30	13.0
Streptococcus faecalis	125	3.2
Clostridium perfringenes spores strain 8798	200	2.0
Clostridium perfringenes vegetative cells strain 8798	75	5.3
Aspergillus niger spores	31	13.0
Poliovirus type 2	185	2.2
Coxsackievirus type B3	200	2.0
Echovirus type 7	170	2.3
Reovirus type 1	165	2.4
Adenovirus type 5	150	2.6
Bacteriophage P22	60	6.6

TABLE III

D_{10} (90 Percent) Inactivation Electron Dose for Various Bacterial Groups In Sludge

	D_{10} Dose (kilorads)	Calculated Log_{10} Reduction for 400 Kilorad Electron Dose
Total bacteria in raw primary sludge	103	4.6
Total bacteria in anaerobically digested sludge	133	3.6
Total bacteria in secondary waste-activated sludge	62	5.6
Total coliforms in raw primary sludge	25	7.6
Total coliforms in anaerobically digested sludge	28	7.2
Total coliforms in secondary waste-activated sludge	36	6.4
Fecal coliforms in raw primary sludge	28	8.0
Fecal coliforms in anaerobically digested sludge	29	8.0
Fecal streptococci in raw primary sludge	157	2.5
Fecal streptococci in anaerobically digested sludge	110	3.6
Clostridia in raw primary sludge	600	0.6
Clostridia in anaerobically digested sludge	500	0.8
Salmonellae in raw primary sludge	26	8.0
Poliovirus type 2 in anaerobically digested sludge	365	1.1
Coxsackievirus type B3 in anaerobically digested sludge	400	1.0
Echovirus type 7 in anaerobically digested sludge	335	1.2
Reovirus type 1 in anaerobically digested sludge	330	1.2
Adenovirus type 5 in anaerobically digested sludge	300	1.3

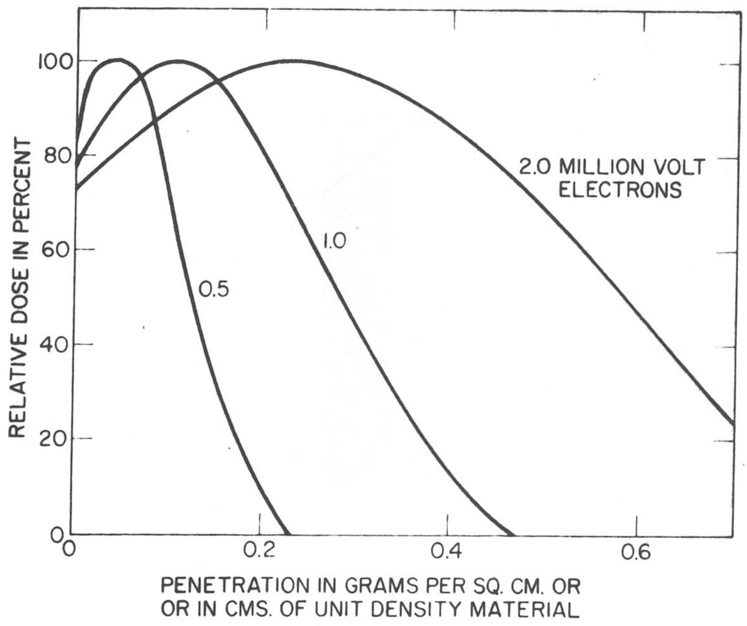

Figure 5. Distribution of Ionization in Water by Mono-Energetic Beams of Several Energies

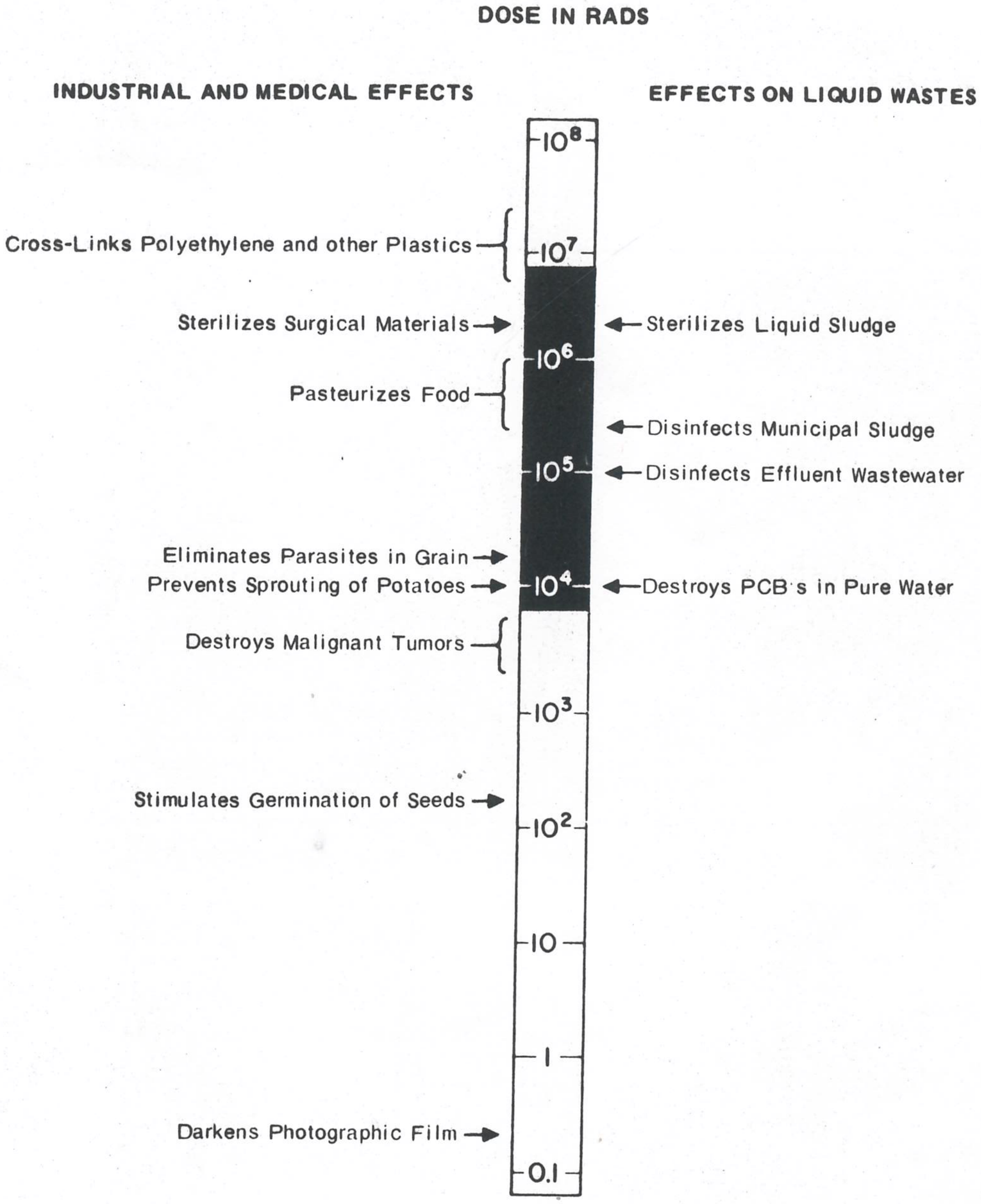

Figure 6. Bar Chart of Radiation Effects as a Function of Dosage

Figure 7. Aerial View of Deer Island

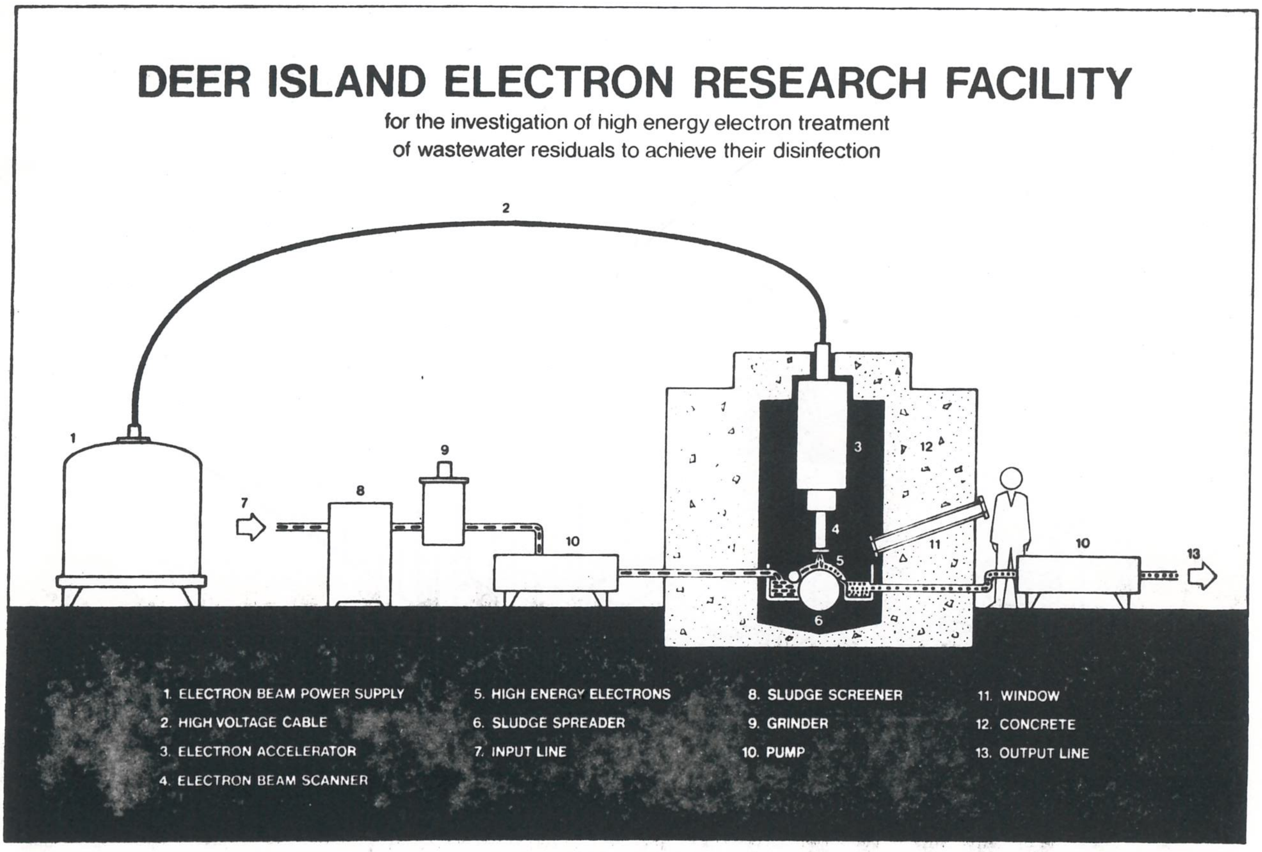

Figure 8. Diagram of the Deer Island In-Line Electron Treatment System

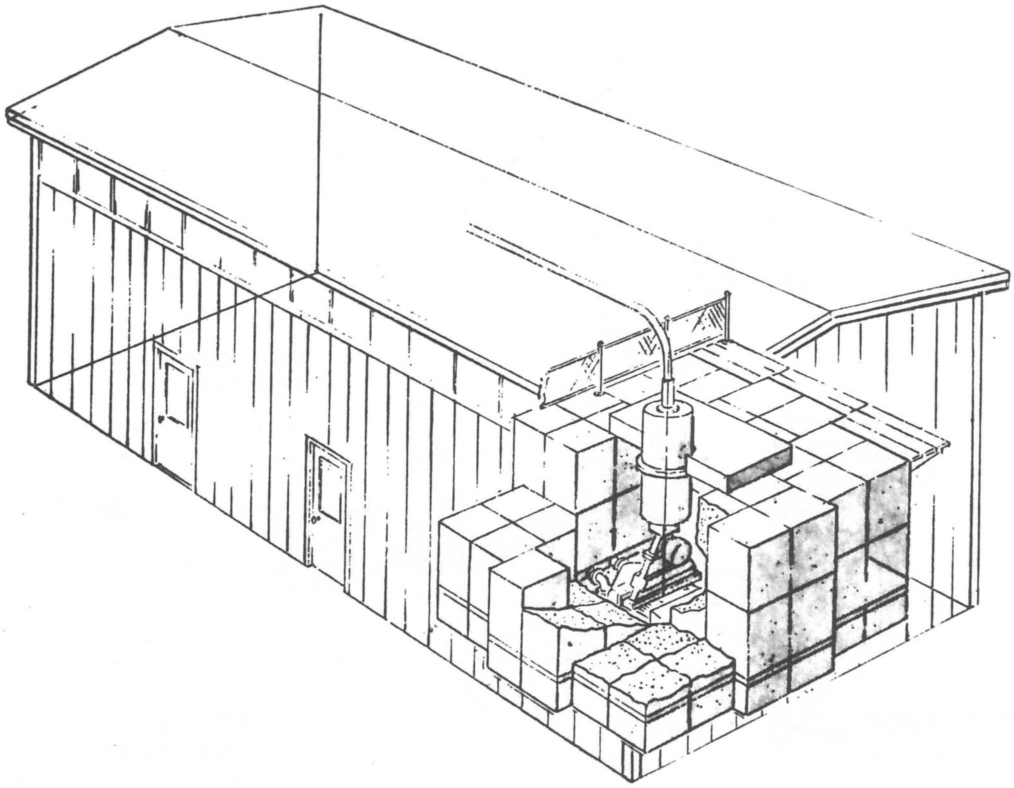

Figure 9. Sketch of Concrete Radiation Shield for Electron Beam Accelerator and Scanner

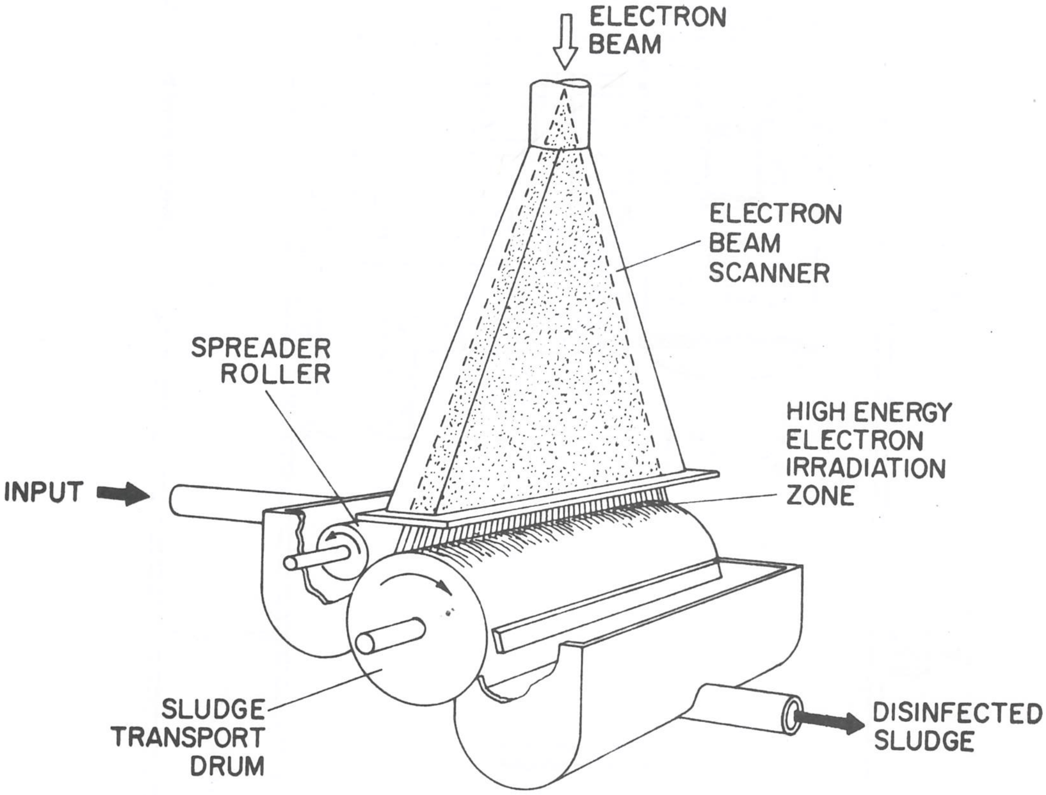

Figure 10. Drum-roll Method of Applying Energized Electrons to a Wide Thin Layer of Moving Sludge

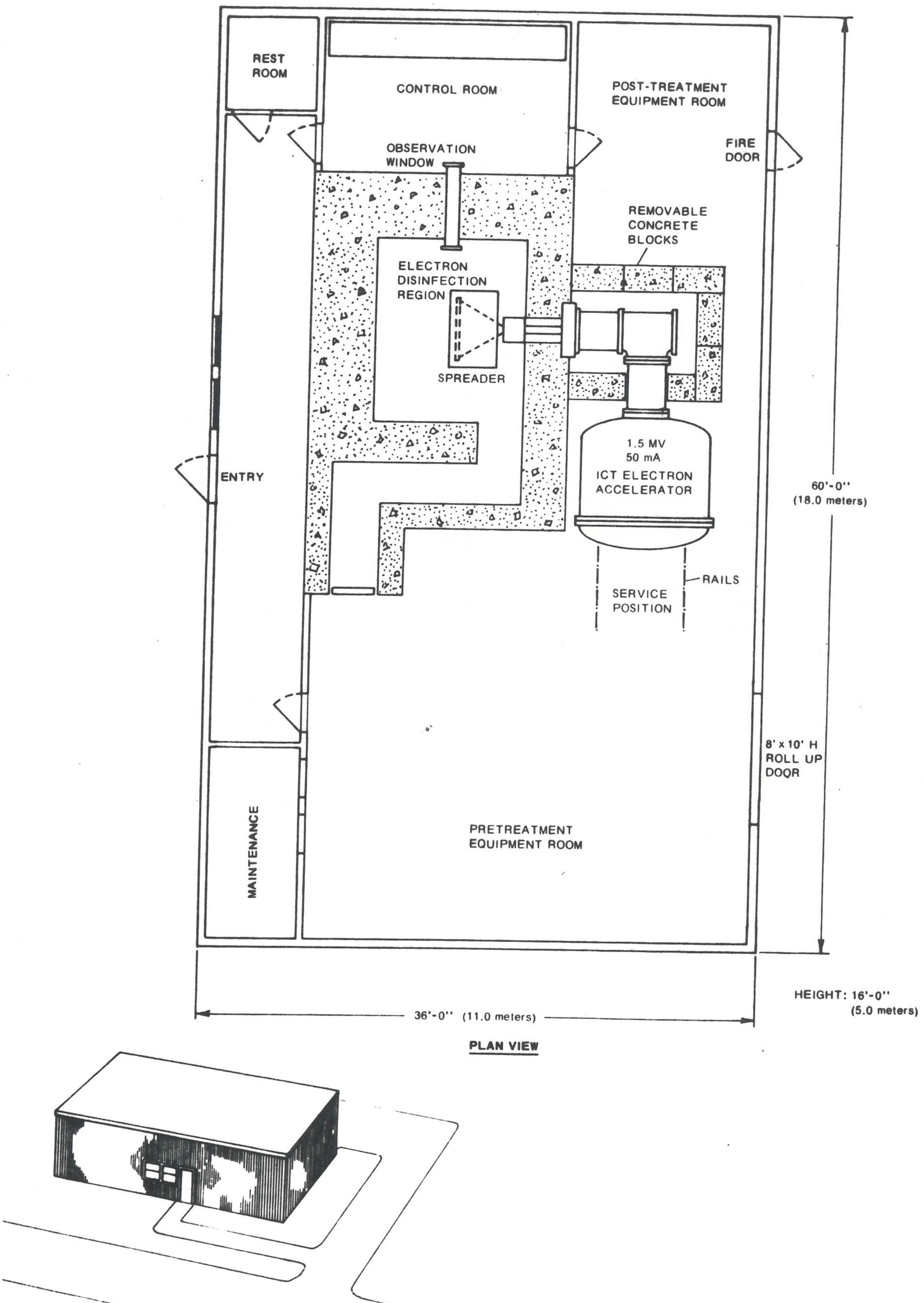

Figure 11. Typical Building Layout for Electron Disinfection of Wastewater/Sludge

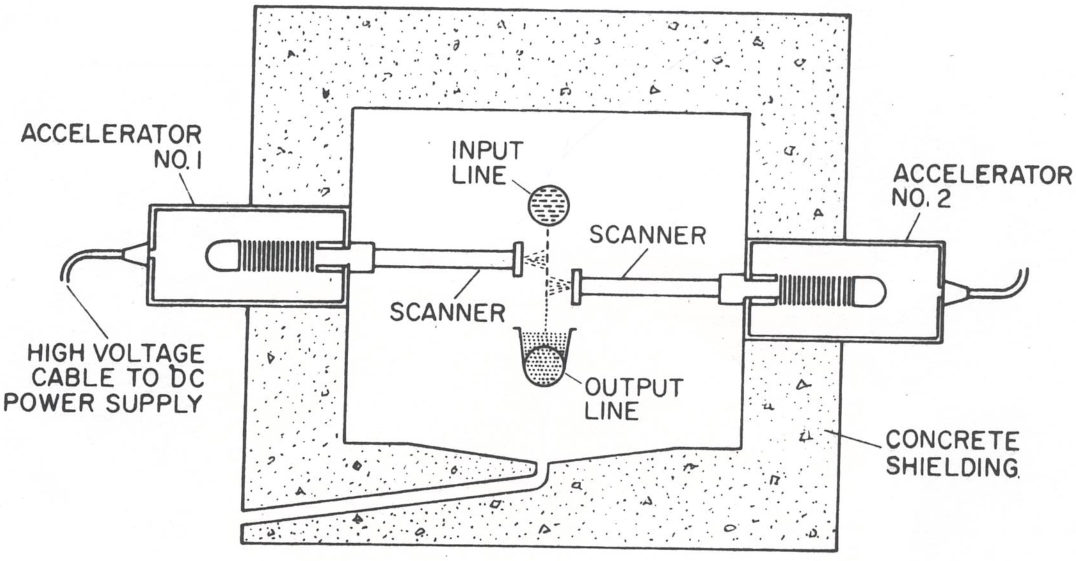

Figure 12. Opposing Portal Injection of Energized Electrons for Secondary Wastewater Disinfection and for Drinking Water Detoxification