

The MIT/Marine Industry Collegium  
Opportunity Brief #32

# Wastewater Management: Technical Alternatives and Regulatory Outlook



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The MIT Marine Industry Collegium

WASTEWATER MANAGEMENT: TECHNICAL ALTERNATIVES  
AND REGULATORY OUTLOOK

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The studies on wastewater treatment reported here were carried out under the direction of Professor John Trump and Alexander Klibanov. The discussion of trends in regulating and financing wastewater treatment facilities was presented by Professor David Marks. The author remains responsible for the conclusions presented herein.

Through Opportunity Briefs, workshops, symposia and other interactions the Collegium provides a means for technology transfer among academia, industry and government for mutual profit. For more information, contact the Marine Industry Advisory Services, MIT Sea Grant at (617) 253-4434/7092.

Margaret Linskey  
July 1, 1983

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## 1.0 INTRODUCTION

Many coastal cities in the U.S. and other countries dispose of their sewage sludge by barge or by wastewater outfall into the ocean. In 1972 the U.S. Congress served notice that ocean disposal of sewage sludge must cease (Public Law 95-153). The final compliance date was later fixed at the end of 1981. To date, not all coastal municipalities have succeeded in implementing acceptable alternatives. Possibilities include disposal on sanitary landfills, incineration followed by landfill disposal of the ash, and composting for restricted land application. Among the problems are lack of accessible land, concerns about environmental risks, and high capital and energy costs.

Although ocean disposal of sludge is against current national policy, new methods of ensuring protection of the marine environment and increasing its fertility could make ocean disposal not only acceptable but desirable in the future. There is now reason to believe that electron treatment, which can satisfy major public health concerns about land application of municipal sludge, can make liquid sludges desirable for use as ocean nutrients.

Wastewater management is a time consuming process that must be concerned with chemistry, with environmental affects and with the political and regulatory environment. At MIT progress has been made in two important technical areas related to wastewater management. The following is a combined discussion and report of the MIT Marine Industry Collegium workshop held at MIT on February 10, 1983. The first area described in some detail in Section 2 below, concerns the use of enzymes for precipitating phenols and related chemicals from industrial wastewater in a new and efficacious manner.

Section 3 describes continued development in the electron irradiation process for treating municipal wastewaters. Professor John Trump describes the progress that has been made since it was last reported in Opportunity Brief #6, Electron Irradiation, Sewage Sludge and Aquaculture and at a Collegium workshop on October 15, 1976. Field tests and actual applications of the process are described here.

Finally, Section 4 compliments the technical alternatives to wastewater treatment presented by Klivanov and Trump. Dr. David Marks spoke about the ramifications of decreased federal subsidization of wastewater treatment plants in an environment of strict regulations and a degrading infrastructure to implement more efficient and ultimately more economic treatment techniques. Professor Marks also discussed the status of Ocean Dumping, the U.S. EPA 301K legislation and toxic materials legislation. Creative financing of sewerage treatment plants might encourage private and public interests to join forces in mutually beneficial partnerships.

## 2.0 ENZYMATIC REMOVAL OF HAZARDOUS POLLUTANTS FROM INDUSTRIAL WASTEWATERS\*

Industrial wastes discharged directly into the oceans off the U.S. coast are estimated conservatively to exceed 5 million tons per year. This input causes concentrations of toxic substances, rapid uptake of contaminants by marine organisms, heavy deposits of materials on the near-shore bottom environment, and excessive growth of undesirable organisms.

Various phenols and aromatic amines are inherent in wastewaters of a number of industries such as coal conversion, resins and plastics, petroleum refining, textiles, dyes and organic chemicals, timber, soaps and detergents, paving and roofing, iron and steel, and ore mining and dressing. Nearly all phenols and aromatic amines are toxic<sup>(1)</sup>. For example, phenols are toxic to fish at levels about 2 mg/l and can cause an unpleasant taste in fish flesh at concentrations much lower than the toxic level. Phenols also have a relatively high biological oxygen demand (BOD) and hence, in sufficient concentrations, can deplete the oxygen in a receiving body of water. Furthermore, a number of aromatic amines such as benzidine and its derivatives, naphthylamines, aminobenzenes, and some others have been determined to be human carcinogens and mutagens. Many others have been recently included by OSHA in the list of suspected carcinogens. Therefore, removal of phenols and aromatic amines from industrial aqueous effluents is of great practical significance.

Existing methods to remove these chemicals from industrial wastewaters include absorption of activated carbon, extraction, microbial and chemical oxidation, incineration, electrochemical techniques, irradiation, etc. These methods, although certainly feasible and useful, suffer from some serious shortcomings such as high cost, incompleteness of purification, formation of hazardous by-products, and low efficiency.

Professor Alexander Klibanov has been studying and has successfully demonstrated the use of enzyme peroxidase from horseradish to remove phenols and aromatic amines from industrial aqueous effluents. The phenols which were tested included phenol itself, o-chlorophenol, cresols, and resorcinol. In all cases treatment resulted in the gradual formation of a precipitate which could be separated easily from the solution by sedimentation or filtration. That is, appropriate treatment results in at least some water purification<sup>(2)</sup>.

### 2.1 Application of Peroxidase for the Removal of Phenols and Aromatic Amines from Water

Suspended solids can be fairly easily removed from water using such simple techniques as sedimentation, filtration, flocculation, or coagulation. These techniques are obviously not applicable to water soluble chemicals, in particular to dissolved phenols and aromatic amines, and therefore much more

\* This material is based on the Doherty Professorship Proposal and Progress Report by Prof. A.M. Klibanov, 1981.

sophisticated and expensive techniques such as adsorption on activated carbon, chemical and biological oxidation, irradiation, incineration, etc. must be employed.

Oxidation of many phenols and aromatic amines with peroxidase and hydrogen peroxide results in the formation of water-insoluble polyaromatic compounds. Hence, phenomenologically the enzyme transforms these toxic chemicals from a water-soluble (up to hundreds of mg/l) into a water-insoluble state. The latter can be eliminated by usual methods employed for removal of suspended solids. Thus, the enzyme peroxidase is used to precipitate toxic pollutants dissolved in water.

From the practical standpoint, it is important to point out that horseradish peroxidase is readily available commercially, fairly inexpensive, extremely catalytically active in a wide range of pH and temperatures, and quite stable. The concentration of  $H_2O_2$  required theoretically is as low as one half of the concentration of the phenols or aromatic amines to be removed.

## 2.2. Preliminary Results of Peroxidase-Assisted Removal of Carcinogenic Aromatic Amines from Water

To demonstrate the feasibility of the approach described above, Klibanov first investigated the application of horseradish peroxidase to remove several carcinogenic aromatic amines from water. The results of this study are briefly reported below.

100 mg/l aqueous solutions of the following carcinogens have been treated with the peroxidase system: o-dianisidine, benzidine, 3,3'-diaminobenzidine, 3,3' -dichlorobenzidine, o-tolidine, p-phenylazoaniline,  $\alpha$ -naphthylamine,  $\beta$ -naphthylamine, 5-nitro -  $\alpha$ -naphthylamine, and 4-amino-biphenyl. In all cases, such treatment results in a gradual formation of precipitate. In order to characterize the peroxidase-assisted removal of the carcinogenic aromatic amines from water and to find optimal conditions for such removal, Klibanov studied in detail the reaction of horseradish peroxidase and  $H_2O_2$  with one of the carcinogens, o-dianisidine (3,3'-dimethoxybenzidine).

Upon addition of  $H_2O_2$  (1 mM = 34 mg/l) and horseradish peroxidase (100 units/l) to 100 mg/l o-dianisidine (pH 5.5) the solution immediately turns dark purple followed by a gradual separation of a brown precipitate. After removal of this precipitate by filtration or sedimentation, a clear colorless solution can be obtained. To find the removal efficiency of this treatment, one can analyze a solution of o-dianisidine before and after addition of the peroxidase system using the diazotation method. The removal efficiency increases along with the time of treatment and in 1 hr. reaches  $99.9 \pm 0.1\%$ . The same removal efficiency was obtained by a direct spectrophotometric determination of o-dianisidine in solution at 279 nm.

It should be pointed out that the treatment of *o*-dianisidine with either  $H_2O_2$  (up to 5 mM) or peroxidase (up to 1000 units/l) alone for up to 24 hours results in no precipitate and in no appreciable decrease in the aromatic amine concentration. Hence the removal of the carcinogen described above should be attributed to the combined action of the enzyme and hydrogen peroxide.

It was of obvious significance to study how the removal efficiency depends on reaction conditions. The efficiency of the enzymatic removal of *o*-chlorophenol from solution has a broad maximum between pH 6.0 and 8.0. Upon reducing the pH to 4.0 the removal efficiency decreases and then increases again in the range of pH 4.0 to 3.0.

The efficiency of peroxidase-assisted precipitation of 0.1 g/liter *o*-chlorophenol (0.8 mM) was investigated as a function of hydrogen peroxide concentration. The removal efficiency gradually increases upon increasing the concentration of  $H_2O_2$  from 0 to 1 mM to reach the level of 99.8% which then remains constant within experimental error at higher concentrations of  $H_2O_2$ .

The removal efficiency for *o*-chlorophenol also increases in proportion to increases in peroxidase concentration. After a 3-h treatment (1 mM  $H_2O_2$ , pH 6.0) it reaches the maximum level at an enzyme concentration of 1 unit/ml. With longer treatment periods, the concentrations of peroxidase needed to reach 99.8% removal efficiency is lower. Thus, with a 24-h treatment, it is less than 0.25 unit/ml. That is, an increase in the time of treatment can be used to offset the reduction in removal efficiency at low enzyme concentration.

An important question was whether the enzymatic removal of *o*-chlorophenol would be as effective at lower concentrations of the pollutant as it is at 0.1 g/liter concentration. The dependence of the removal efficiency on the concentration of *o*-chlorophenol (1 mM  $H_2O_2$ , 1 unit/ml peroxidase, 3-h treatment, pH 6.0) in the range 0.001 to 0.15 g/liter was studied. It was found that within experimental error the removal efficiency is constant in this range.

Thus, it is apparent that peroxidase treatment results in effective removal of *o*-chlorophenol from water under various conditions. The researchers therefore extended the enzymatic treatment to a wide range of other phenols and also aromatic amines. The removal efficiency for each of the aforementioned compounds is reported here at the corresponding pH.

Table I shows the efficiencies of enzymatic removal from water of 16 different phenols. In some cases removal efficiencies are very high (e.g., for *o*- and *p*-chlorophenols, *m*-methoxyphenol, and 2,3 -dimethylphenol), whereas in others they are much lower, in the range of 70 to 95%.



TABLE I

Removal of Various Mononuclear Phenols from Water by  
Horseradish Peroxidase and Hydrogen Peroxide<sup>a</sup>

	Optimal pH	Removal Efficiency <sup>b</sup> (%)
Phenol	3.5	85.3
Guaiacol ( <u>o</u> -methoxyphenol)	5.5	98.0
<u>m</u> -Methoxyphenol	5.5	98.6
<u>p</u> -Methoxyphenol	7.0	89.1
<u>o</u> -Cresol	4.0	86.2
<u>m</u> -Cresol	4.0	95.3
<u>p</u> -Cresol	5.5	85.0
<u>o</u> -Chlorophenol	7.0	99.8
<u>m</u> -Chlorophenol	7.0	66.9
<u>p</u> -Chlorophenol	5.5	98.7
<u>o</u> -Aminophenol	3.5	53.5
<u>m</u> -Aminophenol	5.5	85.3
Resorcinol	3.5	84.1
5-Methylresorcinol	3.5	90.8
2,3-Dimethylphenol	4.0	99.7
2,6-Dimethylphenol	5.5	82.3

<sup>a</sup> Conditions: 0.1 g/liter aqueous solution of phenol, 3-h treatment at room temperature, 1 unit/ml peroxidase, 1mM H<sub>2</sub>O<sub>2</sub>.

<sup>b</sup> At the optimal pH.

The data, which were described at the workshop, allow some conclusions to be reached regarding the relationship between the structure of a pollutant and the efficiency of its enzymatic precipitation. It seems that electron-donating substituents (e.g., methyl or methoxy groups) at the m-position favor the removal to a greater extent than those in o- or p-positions. The situation is exactly the opposite for electron-pulling groups (such as chlorine). An increase in hydrophobicity markedly improves the removal efficiency.

It appears that there are at least two independent factors affecting the overall removal efficiency of a phenol or an aniline from water. The first one is its reactivity toward peroxidase. The second is the solubility in water of the products of peroxidase oxidation. Apparently naphthols have much higher enzymatic removal efficiencies than phenols because polymeric products of the former are more hydrophobic and hence more water-insoluble than those of the latter.

Due to the adverse effect of one (or both) of the two factors discussed above, some compounds listed have relatively low enzymatic removal efficiencies (e.g., phenol, o-aminophenol, aniline, etc.). Moreover, some

phenols, such as *o*-, *m*-, and *p*-nitrophenol, *p*-cyanophenol, and phyrogallol, failed to precipitate as a result of peroxidase treatment. Therefore, it might seem that the proposed enzymatic removal of pollutants would have rather limited application. However, Klivanov et al. have discovered a phenomenon which apparently overcomes this limitation.

They have found that easily removed pollutants (i.e., those that have high removal efficiencies) aid in the precipitation of other phenols and anilines. This phenomenon is illustrated by Table II and III below. One can see that the efficiency of the enzymatic removal of phenol increases dramatically in the presence of easily removable compounds such as *o*-dianisidine or benzidine, and also 8-hydroxyquinoline. Similarly, the peroxidase-assisted precipitation of *o*-aminophenol is enhanced markedly in the presence of easily removable phenols.

There are at least two alternative explanations for the effect described above. Supposing phenol itself is poorly removed because it has a low reactivity toward peroxidase, addition of more reactive compounds would increase the overall yield of free radicals in the system and therefore would result in a higher rate of formation of the polymeric products. An alternative explanation is that phenol may be sufficiently reactive toward peroxidase but the products of its enzymatic oxidation may have a low molecular weight and hence be fairly soluble in water. Addition of easily removable compounds (the products from which are obviously water-insoluble) might result in formation of mixed polymers which are apparently nearly insoluble in water. Currently, the mechanism involved is being investigated in the laboratory.

The discovery of the enhanced enzymatic removal of poorly removed compounds in mixtures of pollutants has an important practical implication. Real industrial wastewaters always contain many different pollutants. Hence, even if just a few of them are easily precipitated by peroxidase, they will facilitate the removal of the others by the enzyme and hydrogen peroxide.

TABLE II  
Efficiency of the Enzymatic Removal of Phenol in the  
Absence and in the Presence of Other Compounds<sup>a</sup>

Pollutant	Added Compound	Removal Efficiency (%)
Phenol	None	74.6
Phenol	<i>o</i> -Dianisidine	99.7
Phenol	Benzidine	99.5
Phenol	8-Hydroxyquinoline	99.8

<sup>a</sup> Conditions: 0.1 g/liter aqueous solution of phenol and other compounds, 1 unit/ml peroxidase, 2.5 mM H<sub>2</sub>O<sub>2</sub>, pH 5.5, 3-h treatment at room temperature.

TABLE III

Efficiency of the Enzymatic Removal of *o*-Aminophenol in the  
Absence and in the Presence of Other Compounds <sup>a</sup>

Pollutant	Added Compound	Removal Efficiency (%)
<i>o</i> -Aminophenol	None	48.6
<i>o</i> -Aminophenol	2,3'-Dimethylphenol	95.1
<i>o</i> -Aminophenol	<i>p</i> -Phenylphenol	92.0
<i>o</i> -Aminophenol	1-Naphthol	84.9
<i>o</i> -Aminophenol	2,7-Naphthalenediol	95.3

<sup>a</sup> Conditions: 0.1 g/liter aqueous solutions of *o*-aminophenol and other compounds, 1 unit/ml peroxidase, 2.5 mM H<sub>2</sub>O<sub>2</sub>, pH 4.0, 3-h treatment room temperature.

### 2.3 Economic Considerations

Any process for industrial wastewater treatment can be practical only if its cost is not prohibitive. At this time it does not seem to be possible to give a precise cost evaluation for the peroxidase treatment suggested above. In fact, this is one of the goals of the proposed project. However, some tentative estimations can be made even now.

It is important to point out that hydrogen peroxide with iron catalysts is presently being used for industrial wastewater treatment to remove such pollutants as phenolics, cyanide, H<sub>2</sub>O<sub>2</sub>, etc. Application of hydrogen peroxide for wastewater treatment has been approved by EPA or is pending in many industries. Therefore, a comparison of the cost of wastewater treatment with H<sub>2</sub>O<sub>2</sub> with an iron catalyst versus H<sub>2</sub>O<sub>2</sub> with horseradish peroxidase is justified.

The market price for 35% technical hydrogen peroxide is about 17 cents/pound or 38 cents/kg = 3.5 cents/mole. For the removal of phenol from industrial wastewaters at least a 5-fold weight excess of H<sub>2</sub>O<sub>2</sub> over phenol should be used. The need to employ such a large excess of H<sub>2</sub>O<sub>2</sub> is due to the fact that the stoichiometry of the process is dependant on the proportions of phenol in water to H<sub>2</sub>O<sub>2</sub>. Hence, if the concentration of phenol in water is 100 mg/l (100 ppm), 500 mg/l H<sub>2</sub>O<sub>2</sub> should be used. Therefore, the cost of the treatment of 1 liter will be  $(38\% * 5 * 10^{-4} / 0.35 = 0.054 \text{ cents.})$

Now let us consider treatment of the same solution with hydrogen peroxide and peroxidase (using as an approximation the data on peroxidase-assisted removal of *o*-dianisidine reported in the previous section). First, the amount of H<sub>2</sub>O<sub>2</sub> needed is much lower; 0.6 mmoles = 20 mg is sufficient to provide 99.9% removal. 20 mg of H<sub>2</sub>O<sub>2</sub> will cost only 1/25 as 500 mg or 0.54/25 = 0.002 cents. It is much more difficult to estimate the cost of horseradish

peroxidase, because this enzyme is not currently used in industry and therefore is not produced in bulk quantities. However, the upper limit can be calculated. In accordance with the "Miles" Catalog, if one purchases 125 g of horseradish peroxidase (Code No. 36-455-2) 1 unit of catalytic activity will cost 0.05 cents. As one could see in the previous section, in the case of o-dianisidine removal, peroxidase concentrations is as low as 0.3 units/l are quite effective. Therefore, the cost of the treatment of 1 liter of an effluent will be  $(0.05 \text{ cents} * 0.3) + 0.002 \text{ cents} = 0.017 \text{ cents}$ , which is comparable (in fact, lower) than the cost of the treatment with  $H_2O_2$  and iron. The most important factor, however, is that if (i) there is a demand for horseradish peroxidase in industry, and (ii) a crude preparation of the enzyme is to be employed, the price for the enzyme will decrease by up to an order of magnitude. This factor can be derived if one compares the prices for two industrially used oxidoreductases; glucose oxidase and catalase, charged by a laboratory supplier (e.g. "Miles" or "Sigma") and by an industry supplier (e.g. "Novo").

It should be mentioned that if the treatment of industrial wastewater described above is practical and economically beneficial, the horseradish peroxidase might be eventually replaced by a bacterial enzyme with similar catalytic properties.

### 3.0 WASTEWATER TREATMENT BY ELECTRON IRRADIATION

The issues of wastewater treatment and treatment of the residual sludge have not changed drastically since 1976, when Professor John Trump first presented his data to the Collegium on the effectiveness of irradiating electrons to disinfect sewage sludge. Chlorination, incineration, and land and ocean disposal of sludge are still practiced in varying degrees all over the U.S. However, the U.S. EPA guidelines published in the November 1977 Federal Register included for the first time "the use of penetrating ionizing energy to reduce the bacterial, parasitic and viral contents of sludge to those attainable by conventional, biological treatment methods." Consequently, electron irradiation of sewage sludge was added to the list of municipal wastewater treatment methods.

Growing concern over the environmental effects and public health risks of chlorinated sewage effluents has stimulated the search for safer and more effective disinfection alternatives. For several decades laboratory-scaled studies have shown that moderate doses of ionizing energy can destroy bacterial pathogens in sewage.

In 1980 MIT with the cooperation of the High Voltage Engineering Corporation (HVE) completed a six-year investigation of the physical, biochemical and economic feasibility of disinfecting liquid municipal sludge by energized electron irradiation. Initiated with Sea Grant funds, and supported in large part by the US National Science Foundation, this comprehensive study also included contributions by virologists of the University of New Hampshire and plant scientists of the University of Massachusetts.<sup>(3)</sup>

The major engineering goal of the MIT, NSF, HVE project was to achieve a reliable in-line, high-flow-rate system for liquid waste disinfection by electron injection, under realistic operating conditions. For this purpose, an electron facility initially designed to treat up to 100,000 GPD of digested liquid sludge or effluent wastewater was set up in 1976 at Boston's largest wastewater treatment plant on Deer Island. Bacterial and viral disinfection studies and operational studies were carried out until 1981.

Later this research facility was re-equipped and powered by a 1.5 million volt (MV) electron accelerator with 75 kW of electron beam output. The liquid sludge disinfection capability of the unit has been demonstrated at flow rates up to 200,000 GPD, treating half the daily anaerobically digested sludge produced by the MDC Deer Island wastewater treatment plant which services a large part of Boston and over a score of surrounding communities.

### 3.1 The Process of Ionizing Energy: A Disinfection Alternative

The six year study has shown that injection of machine accelerated electrons into liquid sludge collected from sewage wastewater is effective in destroying disease-causing microorganisms. A wide, thin stream of watery sludge flows through an intensely ionizing electron beam which is scanned to distribute its energy throughout the stream cross section. The intense ionization destroys bacteria, viruses and parasites, and promotes the degradation of toxic organic compounds. Electron treatment of effluent wastewater (as distinct from liquid sludge) has even more modest energy requirements and can support or replace chlorination with important environmental benefits.

Wastewater disinfection requires applied voltage of one million or more volts to accelerate electrons in vacuum to velocities close to the speed of light. The electrons penetrate to a depth which varies inversely with density and directly with the accelerating voltage. For water and watery sludge, the maximum depth is about 1 cm for each 2 million volts. Each electron produces about 30,000 ionizing collisions per million volts before it is brought to rest.

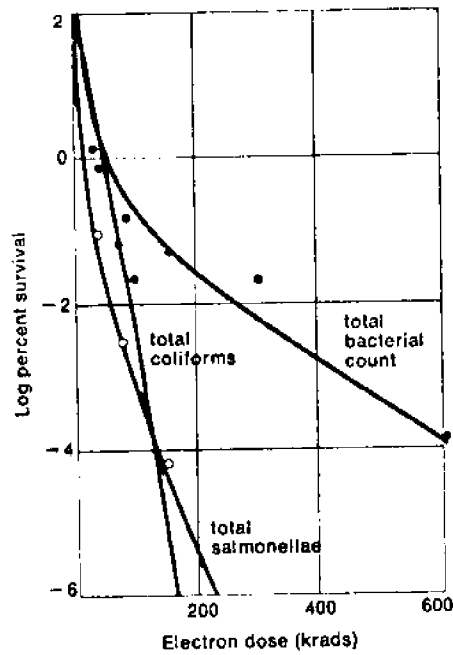
The delivery of a 50 kilorad (a rad is a measure of absorption of radiation energy: 1 rad = 100 ergs/gram) dose has been found to be adequate for effluent wastewater disinfection. This is accomplished in less than 1/100th of a second as it flows in a wide thin stream through the scanning electron beam. Since all of the water must receive at least the desired dose, the electron beam must scan the full stream width and penetrate the water thickness.

"Although 50 kilorads results in an insignificant temperature rise in watery material, it produces a formidable measure of well distributed highly reactive products. In each gram, 50 kilorads ionizes  $3 \times 10^{18}$  molecules and excites to a higher energy state many times more. It also dissociates  $10^{19}$  water molecules into highly reactive  $H^+$  and  $OH^-$  radicals. These energy-transferring, bond-cleaving events constitute "hot chemistry" on a molecular scale. All of the energized molecules and dissociated fragments react avidly with each other and with nearby dissolved and suspended matter. These in turn may react with still other molecules until a new order of chemical and energy stability is restored. Some of the energized products participate in the formation of ozone and hydrogen peroxide which are themselves powerful oxidizing agents".(4)

Viruses, for example, succumb to the combined attack of these secondary agents on their viral coat and on their nucleic acid interior. Bacteria, eggs and larvae of parasites, and clumps of particulate matter are likewise surrounded and permeated with the momentarily energized and reactive products. A few molecular alterations result in the destruction of their viability.

Extensive biological assays produced convincing evidence of the disinfection efficiency of energized electrons. A dosage of 400 kilorads was found to be adequate to disinfect wastewater sludges. Disinfection of all sludges is essentially independent of pH, organic content, temperature, or the presence of particulate matter. 400 kilorads of absorbed ionizing energy reduces the total bacterial count by 4 to 5 orders of magnitude and reduces to undetectable levels the Gram-negative group of bacteria which contains most of the bacterial pathogens. The 400 kilorad dose also reduces viral populations by one to two orders of magnitude. The bacteria of greatest concern -- coliforms and salmonellae -- are among those most easily destroyed by electron treatment. Figure 1 shows that the number of surviving microorganisms in sewage sludge diminishes almost exponentially as the electron dose is increased.

Figure 1: Relation Between Number of Surviving Microorganisms in Sewage Sludge and Electron Dose



Source: Trump, "Energized Electrons Tackle Municipal Sludge," 1981.

### 3.2 Case Studies of Wastewater Treatment by Electron Irradiation

#### Deer Island Pilot Plant

Recent high-flow rate studies on effluent wastewater at the Massachusetts Metropolitan District Commission sewerage treatment facility at Deer Island by High Voltage Engineering have shown that less than 50 kilorads is sufficient for disinfection. Table IV shows typical counts of bacteria in anaerobically digested sludge at Deer Island before and after the radiation. At a dose of 50 kilorads the disinfection of municipal wastewater by electrons becomes an economic and energy-efficient alternative.

Table IV  
Typical Counts of Bacteria in Anaerobically Digested Sludge  
at Deer Island

Type of Bacteria	Count per ml	
	Before Electron Treatment	After 400-krad Dose
Total Bacteria	$4 \times 10^6$	$10^2$
Total Coliforms	$8 \times 10^5$	bd1 <sup>a</sup>
Fecal Coliforms	$1 \times 10^5$	bd1
Salmonaellae	$4 \times 10^1$	bd1
Fecal Streptococci	$5 \times 10^3$	10
Clostridia	$6 \times 10^4$	$10^2$

<sup>a</sup> Below detectable level

Source: Trump, "Energized Electrons Tackle Municipal Sludge", 1981.

The capacity of the present Deer Island electron system, for example, would increase to about 2 million GPD for effluent wastewater, up from the 200,000 GPD for liquid sludge. A 50 krad dose raises the water temperature only 0.12 C., whereas a 400 krad dose of absorbed energy raises the water temperature about 1 C.

There is now evidence that electron disinfection can significantly diminish water-dissolved toxic compounds such as pesticides and herbicides. MIT studies of the effects of energized electrons on toxic chemicals showed that trace polychlorinated biphenyls (PCB's) and certain pesticides in pure water are destroyed by remarkably low doses. Similar destruction at low electron doses of several other trace toxic chemicals in water solution has now also been observed. Trace toxic compounds in water/lipid mixtures, however, were found to require progressively higher doses, the higher the



lipid fraction. Since 1972 the Metropolitan District Commission in Boston has been studying alternatives for disposal of its municipal sludge. At present, both the Deer Island and Nut Island wastewater treatment plants are timed to discharge their anaerobically digested sludge into the chlorinated effluent wastewater during periods of outgoing tide. Deer Island, the narrow peninsula that forms the northern boundary of Boston Harbor, is surrounded by a densely populated area on the land side. Because no land is available for sludge composting or disposal, MDC, on the advice of consultants, proceeded with plans for incineration of the combined Deer Island and Nut Island sludges as its only feasible alternative. The final Environmental Impact Statement, published in March 1979 after several years of preparation, supported incineration as an interim solution but recommended a continuing search for better alternatives.

### Miami Dade Water and Sewer Authority

The Miami Dade Water and Sewer Authority is constructing an electron disinfection system that is capable of irradiating 170,000 gallons of anaerobically digested liquid sludge per day at its Virginia Key Wastewater Treatment Plant in Miami. Selection of this method by the Authority and its funding by the U.S. Environmental Protection Agency were based to a large extent on the successful demonstration of the high flow rate studies performed at Deer Island. The Miami Dade demonstration system is planned to begin by July 1983. In one of the planned applications, the disinfected sludge will be distributed over a former solid waste site that is covered with a thick layer of coral sand. Water, humus and plant nutrients distributed over this area by subsurface injection of the disinfected sludge could transform this coral desert into fertile and attractive recreational land in a few years. For coastal cities without adequate access to land, widespread dispersion of disinfected material in selected ocean water could enhance the nutrient content and increase the regional fish populations.

### 3.3 Economics of Modular Electron Disinfection Systems for Wastewater (5)

A 200 kW electron beam system powered by a 2.5 MV accelerator could treat 6 million gallons per day of wastewater to a "least" dose of 50 kilorads. The electrons would be injected into the full width and thickness of a downward moving stream. At the electron injection zone the stream would be 4.5 m (15 feet) wide, up to 1 cm thick, and moving at the rate of 6 m (20 feet) per second. The beam, carrying 80 milliamperes of energized electrons, would be scanned in the horizontal plane across the stream width at a frequency of 1000 gallons per second to achieve approximate uniformity of dose over the entire water surface and throughout its volume.

Such a modular, 6 million GPD facility could be housed within a 300 M<sup>2</sup> building and would utilize about 300 kW of conventional AC electric power. Larger disinfection capacity is obtained by paralleling identical modules. A 30 million GPD system, for example, would consist of 5 essentially independent modular units with advantages in load adjustability, redundancy and manufacturing cost.

Capital cost in 1981 dollars for such a 6 million GPD modular treatment system is estimated at \$2 million. The annual cost for continuous full-load operation, including capital recovery over 20 years, electric power, supervision and maintenance, is estimated at \$500,000 or 23 cents per 1000 gallons<sup>(6)</sup>. Excluding capital recovery expenses, the cost of electron disinfection by a dose of 50 kilorads is about 14 cents per 1000 gallons. The gross electric energy required for wastewater disinfection at 50 kilorads is about 1.2 kWhr per 1000 gallons.

During the 1970's, the costs of wastewater chlorination and dechlorination increased whereas the cost of electron beam power steadily declined. As a result, these two alternative methods for wastewater disinfection are now within economic sight of each other. Electron disinfection now comes within a factor of 10 of matching chlorination costs and further substantial cost reductions are expected. The expected increase in unit power output and increased efficiency of electron accelerators during the 1980's could result in a further threefold lowering of the cost per kW of electron beam power. These anticipated advances in technology, coupled with its inherent long-range health and environmental benefits, should weigh the choice for wastewater disinfection in favor of electron treatment.

#### 4.0 NEW TRENDS IN FINANCING WATER AND WASTEWATER PROJECTS

The following is a discussion paper presented by David Marks, Professor of Civil Engineering at MIT.

From 1981 to present, two significant trends have developed in the provision of water supply and the treatment of wastewater that bear serious concern for those who must provide and pay for such services. For those involved in water supply, the past two years have been characterized by the phrase "America in Ruins." This term refers to the realization that much of America's water infrastructure, in particular the pipes that carry water from treatment to use are old and in bad repair. Service interruptions are increasing in frequency, valuable water is being lost via leaks in failing water pipes and the possibility of public health impacts from drinking water contacting impurities due to leaks are all occurring. Estimates of the finances needed to fix them go as high as 800 billion dollars. This problem has occurred because of the relatively low priority given to maintenance, repair, and rehabilitation of the existing systems as well as the need to upgrade treatment in the face of newly discovered chemical threats to public health. Water utilities have traditionally charged low rates to protect the public against potential unsafe private water suppliers. However, existing rates have not been sufficient to provide for the escalating costs of equipment replacement and repair. Repairing existing infrastructure has never been very "sexy" compared to building new facilities, especially at election time.

The question that should be posed is where will the funding for such repairs originate, since it may be much more than utilities can hope to raise through existing means? In water supply there has never been a history of federal subsidy, because to date it was considered a purely local matter. Nor does it seem in these times of hard priorities that such funds will become available. However, the problem is not as bleak as it seems. First, the estimates of needs are probably inaccurate, in this case on the high side. The needs were determined by considering that all old infrastructure (say over 60 years) must be replaced by facilities of the same type. It is not clear that all old facilities need replacement, nor that exactly the same facilities would replace them. This is a time to consider a host of rehabilitation, repair and maintenance strategies, as well as replacement. How are such strategies identified and the money found to implement them?

A problem of a somewhat different nature is the provision of wastewater treatment. Federal and state subsidies have taken a major role in providing this function, and in the past up to 90% of the cost of such facilities was subsidized. However, such subsidies did not come without some negative side effects. The review process for grants was so long, multi-tiered and tedious that projects were delayed many years leading to increases in costs due to inflation and redundant planning. In addition, in attempting to standardize what the public was paying for, federal regulations took away a great deal of planning flexibility made possible by favorable local conditions. The

disappearance of such subsidies of course has hindered the development of new facilities. Why invest now with one's own money if there is a chance the subsidies might come back? Also, going from 10% to 100% of costs is a quantum jump in financing needs. It is interesting that when water supply professionals are queried about federal funding, most would like to have it provided it is structured by a process that minimizes time delays and inefficiencies.

How are such projects now to be funded? The answer seems to be evolving from a series of novel, perhaps even strange approaches, that are collectively called "creative financing". A topic attracting considerable attention these days is "privatization": having private firms build facilities and provide services. Some examples are based on the SAFE Harbor Leasing Act of 1981 which allowed businesses accelerated depreciation on capital goods. Why not have industry buy the things government needs and lease them to government? In this case the industry can depreciate the value of the equipment and hence receive a hidden government subsidy through lower taxes. Such examples have taken place in the transportation industry where, for instance, the New York MTA Metropolitan Transportation Authority has sold its buses to Metro Media and then leased them back. The MTA received a large one-time infusion of cash and was able to lease the buses at a cost lower than ownership. Similar cases in the selling of water systems are likely to occur in the near future.

The concept of the private sector contributing a major portion to building a much larger infrastructure needs more study. In this case a contractor might agree to provide needed facilities, finance them and operate them after completion for a set fee. Money to build such facilities might come from "infrastructure banks." These banks are set up by government grant and/or bond issues and would provide reasonable credit loans for building public infrastructure either by the public sector or by private groups who would be under contract to the public sector. By using low cost revolving loan funds, thereby enhancing the process of efficient, timely construction, it may be possible to build more quickly and with less cost. With a less expensive facility producing services and hence revenues more quickly, lost subsidies become irrelevant.

There would appear from the above discussion to be developing a great opportunity for entrepreneurs to invest in building infrastructure at reasonable cost. As of yet, no predominant trend has developed. It is too soon after the traumatic loss of federal involvement for a majority of local and state entities to realize that these monies probably will never flow again regardless of the administration, and that such facilities must be provided in any event. Within a few years, one would expect to see a firmly established infrastructure bank concept and a very strong link between the public sector and private sector lending, building, and entrepreneurial institutions to jointly combat these problems to satisfy both the public good and private profit motives. Thus, the silver lining of the dark cloud caused by "American Ruins" and the end of federal funding may well be a strong, better controlled and more cost effective movement toward infrastructure provision and replacement.

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