The MIT/Marine Industry Collegium

Opportunity Brief #6

ELECTRON IRRADIATION, SEWAGE SLUDGE AND AQUACULTURE

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The MIT Marine Industry Collegium

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1.0 A BUSINESS PERSPECTIVE

One of the key problems of disposing of sewage sludge on land or in the oceans is the transmission of disease. Raw sewage containing animal wastes carries a variety of disease causing organisms that are not removed by conventional treatments. In fact, the primary and secondary sewage treatments used today serve to concentrate the pathogens in sludge.

Sludge can be constructively recycled and used as a fertilizer. However conventional sterilization by heating requires such large amounts of energy that sludge conversion to fertilizer is economical in only a few exceptional cases (where inexpensive energy is available, for example, or where other means of disposal are unusually expensive).

With support from the MIT Sea Grant Program and the National Science Foundation, Professor John Trump and his associates at MIT have developed techniques for sterilizing wastewater and sludge by high-energy electron irradiation. Laboratory experiments have shown that electron irradiation is effective in eliminating pathogens and uses only a fraction of the energy required in heat sterilization. An experimental pilot plant for sludge irradiation has recently been placed in operation at the Deer Island wastewater treatment plant in Boston Harbor.

The development of low-cost sludge sterilization has potentially interesting commercial applications in several areas. For municipal wastewater treatment facilities, irradiation offers an opportunity to generate commercially valuable, pathogen-free fertilizers or soil conditioners. Waste disposal systems aboard ships, on ocean platforms and in marinas represent a potentially large though specialized market for irradiation systems.

Of possibly greater significance is the impact that economical sterilization procedures could have on existing methods of waste disposal. The elimination of pathogens from sludge could well provide a basis for reexamining the current restrictions on dumping, both on land and in the ocean. If sludge could be made disease-free, benign ocean dumping procedures might be developed. Conceivably, we might even have a valuable new tool for aquaculture--fertilizing the ocean to increase yields of fish or plant life.

In this Brief, we review the current state of electron irradiation as a sludge sterilization method. We compare its costs with existing methods and make some economic projections about the production and sale of sludge as fertilizer. Finally, we outline some of the potential opportunities for industry. We focus especially on opportunities that could result if irradiation were to become widely accepted and aquatic disposal were to become widespread.

2.0 THE SLUDGE DISPOSAL DILEMMA

While the enactment of the Federal Water Pollution Control Act Amendments of 1972 has resulted in cleaner effluents, it has also resulted in an increase in the quantities of sludge left as a residual of sewage treatment.

Primary and secondary wastewater treatment in the United States alone leaves a residue of more than 250 million tons of wet sludge a year. It has to be put somewhere. We can dump it in the ocean, spread it on land, or put it into the air (by burning it). As things now stand, each of these disposal methods has associated problems.

Ocean dumping has been the obvious solution for many coastal cities. However, the present law (Marine Protection, Research and Sanctuaries Act of 1972) prohibits ocean dumping without prior permits and the institution of costly compliance procedures and prohibits ocean dumping after 1980 (1).

Burning and pyrolysis are being studied seriously in many areas. However, the costs of drying and incinerating sludge are becoming prohibitive as the price of energy soars. Burning also creates problems of air pollution, odor, and disposal of the ashes.

Land disposal raises several public health and environmental problems. Nitrates in the sludge can pollute the ground water, and metals may become absorbed into crops.

A potentially more serious threat than any of the problems summarized above is that of disease dissemination during or after disposal. Disease-causing organisms are concentrated in the sludge during primary and secondary treatment. Several studies have found that viruses and pathogens have considerable staying power, continuing to live for several weeks after disposal (2,3,4,5). It is the threat of disease that reinforces the relevance and urgency of MIT's research into the irradiation of sludge for sterilization.

3.0 AN INTRODUCTION TO HIGH-ENERGY ELECTRON IRRADIATION

Electrons in a vacuum can be accelerated to approach the velocity of light. Moving as a beam of directed particles, these high energy electrons can be passed from the vacuum, through a thin membrane, and into some target material. They will penetrate solid or liquid matter and distribute their energy by exciting and ionizing the trillions of atoms and molecules along their paths. High-energy electrons can penetrate water up to depths of about one centimeter for each 2 million electron-volts (MeV) of energy.

Over the past two decades, high-energy electron irradiation has been shown to be capable of controlling bacteria and viruses in waste liquids and solids (6-12). Applications have also been demonstrated in food preservation, sterilization of surgical materials, and control of hepatitus in blood plasma.

3.1 Electron Irradiation of Sewage Sludge. Work at MIT has shown that high-energy electron irradiation is an effective means of treating wastewater and sewage sludge. Following two years of research, an experimental sludge irradiation facility is now being operated at the Deer Island wastewater treatment plant in Boston Harbor. The facility uses a commercially available 50-kilowatt, 750-kilovolt electron accelerator with a high-speed scanner. Disinfection by means of high energy electrons requires that the ionizing energy be uniformly distributed among the atoms and molecules of sludge. The system, shown in Figure 1 (page 6), achieves uniform irradiation by moving a wide (120 cm) thin (2 mm) band of 5% sludge past the electron scanner at 2 meters per second.

The electron energy, redistributed among the atoms and molecules of

FIGURE 1

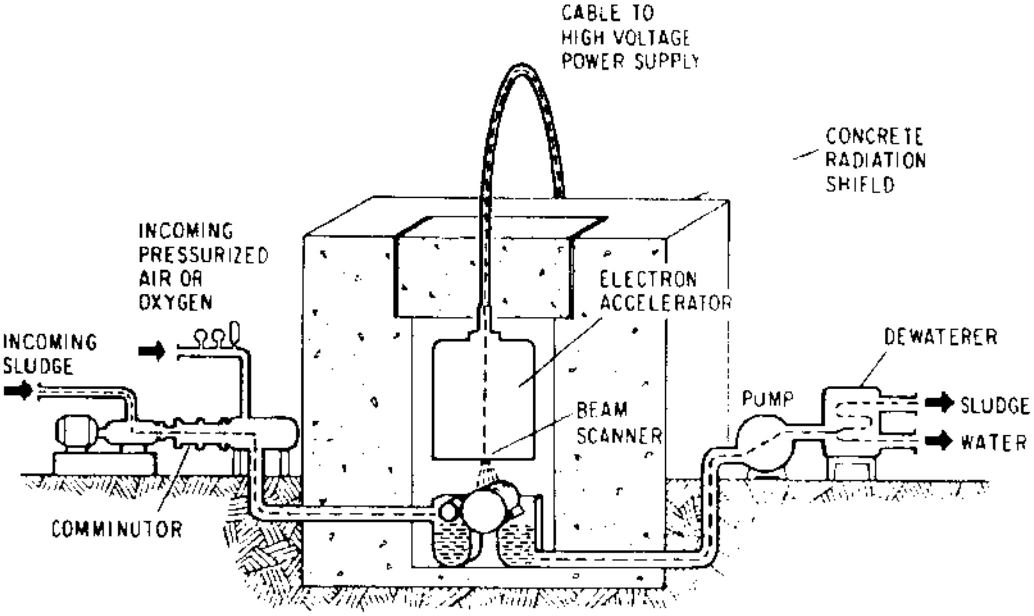
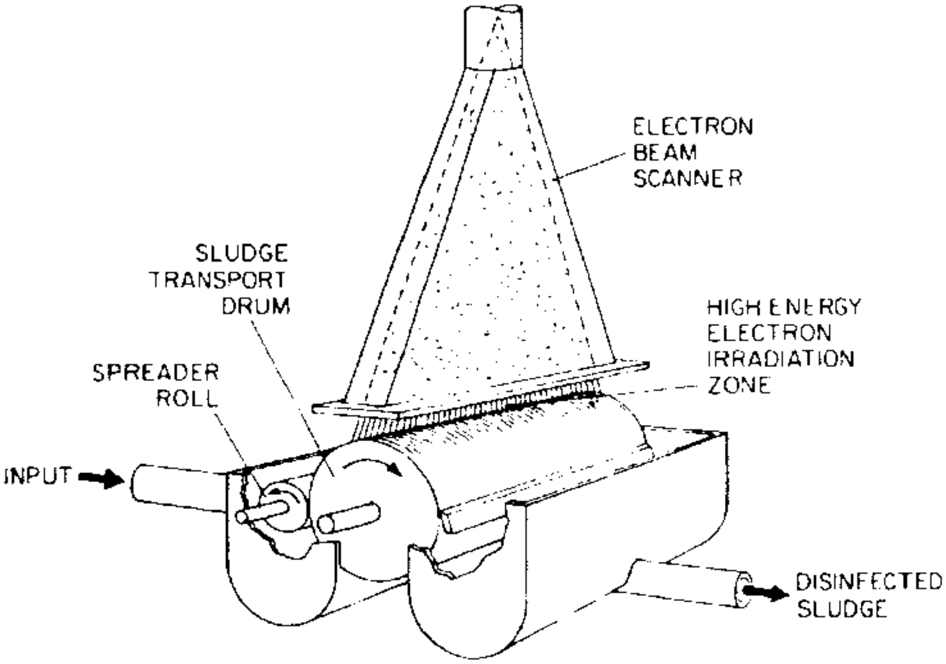


Diagram of In-Line Sludge Flow through Deer Island Electron Treatment Facility.



Method of Applying High Energy Electrons to a Wide Thin Layer of Moving Sludge.

contaminated water, produces the highly reactive free radicals, H^+ and OH^-. These in turn attack entrained molecules to promote their oxidation, reduction, disassociation, and degradation. The free radicals may combine to form hydrogen peroxide and ozone, which are themselves useful for water treatment. Simultaneously, the ionization exerts a direct lethal effect on microorganisms (bacteria, viruses, spores, and molds) and on larger organisms, including algae, protozoa and parasites.

In addition to sterilizing, enhancing oxidation, and increasing biodegradability, electron irradiation changes the colloid systems in the sludge to improve settling and to facilitate dewatering, especially when used in concert with certain inexpensive benign dewatering chemicals. Irradiation may also change heavy metals into less soluable compounds. These effects are currently under study.

A further benefit of electron irradiation is that the biochemical effects are essentially completed in the fraction of a second during and immediately following the electron injection. Since electrons penetrate the sludge, the desired changes occur within the sludge and not just on the surface. The thoroughness of irradiation contrasts sharply with conventional surface active chemicals such as chlorine which have a slow sterilizing effect that depends on adequate diffusion for disinfection (13).

3.2 Side-Effects of Electron Irradiation. Irradiation of sludge or water by low megavolt electrons results in a slight increase in sludge temperature due to the absorbed energy. Otherwise, the process has no adverse side-effects. The temperature rise is about 1° Centigrade for sludge treatment at the levels required for sterilization (14).

Electron Irradiation at the doses and energies required for sterilization does not increase the natural radioactivity of water. The lowest energy thresholds for the onset of neutron production (and hence possible radioactivity) by electron bombardment are 2.2 MeV for Deuterium and 1.67 MeV for Beryllium. These elements are not typically present in sludge to any appreciable degree. Since the accelerator voltage is only 0.75 MeV, induced radioactivity is almost absolute zero (15).

X-rays are produced whenever energetic electrons are decelerated. However, the x-rays produced by the Deer Island irradiation system are contained within a shielded vault and fall well within the permissible levels of national safety standards (16).

3.3 Electron Irradiation Versus Radioactive Isotopes. Radioactive isotopes such as Cobalt 60 and Cesium 137 may be used to sterilize sludge. However, this method has severe disadvantages when compared to energized electrons.

First, high-energy electrons have fundamental safety advantages over isotopes. When an electron accelerator is turned off, it instantly ceases to emit high-energy electrons. By contrast, radioactive sources of gamma rays emit continuous radiation and must be contained within shielded vaults during their lifetimes. Accidental or malicious dissemination of the ionizing energy from an electron accelerator is virtually impossible, whereas radioactive isotopes pose a threat in the event of operating accidents, earthquakes or sabotage.

Second, the desired sterilizing effects of Cobalt 60 radiation must be achieved by recirculation and longer periods of irradiation. The flow-through method used in the electron irradiation process is significantly faster. Batch processing must be used for the Cobalt 60 radiation to be effective. In 1973, a prototype plant using Cobalt 60 was placed in operation near Munich, Germany. The plant uses a radioactive isotope source of 114,000 curies. The process initially took about 5 hours for a $6m^3$ batch or a daily capacity of $30m^3$. The source has since been increased to decrease batch time, resulting in a daily capacity of about $150m^3$, which is equivalent to about 40,000 gallons per day, or less than half that of the Deer Island plant (17).

Third, high energy electrons enjoy a significant cost advantage over Cobalt 60 irradiation. Table 1, page 10, compares sludge irradiation costs of the Deer Island plant with costs of Cobalt treatment for a plant of the same dosage and capacity. The electron irradiation process is less than half as expensive as cobalt isotopes, owing to lower capital cost and lower operating costs.

3.4 Estimated Cost Data. The pilot project at Deer Island will establish a firmer basis for economic evaluation of electron treatment. Estimates of capital and operating costs in Table 1 were based on the following assumptions: that 400,000 rads is an adequate disinfection dose for sludge (studies may show that this dose can be reduced), and that the overall electron utilization efficiency is 35% (indications are that it could be 50-60%). Under these conditions, 50 kilowatts of beam power can treat 100,000 gallons of sludge in a 24 hour day.

TABLE 1

COMPARATIVE SLUDGE IRRADIATION COSTS

	COBALT 60	ELECTRONS
Assumptions		
Disinfection Dose	400,000 rads	400,000 rads
24 Hour Sludge Throughput (100,000 gallons)	375m^3 420 tons	375m^3 420 tons
Radiation Source Strength	1,750,000 curies	50 kilowatts
Radiation Utilization Efficiency	70%	35%
Capital Costs		
Source Cost	$875,000 (at 50¢ a curie)	$300,000
Facility Cost	150,000	150,000
TOTAL CAPITAL COST	$1,025,000	$450,000
Annual Operating Costs		
Cobalt Annual Renewal at 12.5%	109,375	
Electron Accelerator Power (3¢/kw hr.)		18,000
Auxiliary Electric Power	6,000	3,000
Supervision and Maintenance	82,000 (at 8%)	54,000 (at 12%)
Amortization	51,250	22,500
Interest on unpaid balance at 10%	51,250	22,500
TOTAL OPERATING COST	$299,875	$120,000
Unit Costs		
Cost Per WET TON	$1.96	$0.78
Cost Per 1000/gal.	8.22	3.29
Cost Per DRY TON (based on 5% solids)	$39.20	$15.60

COST RATIO 2.5

Data extrapolated from:

Trump, J.G., et al. Prospects for High Energy Electron Irradiation of Wastewater Liquid Residuals. Cambridge, MA: MIT, 1976 [MIT Sea Grant Report No. 75-19].

Ballantine, D.S. "Alternative High Radiation Sources for Sewage and Wastewater Treatment." Radiation for a Clean Environment: Proceedings of a Symposium, Munich, Germany, March, 1975. Vienna: International Atomic Energy Agency, 1975, IAEA-SM-194/501.

The figures have been updated by a September 1976 conversation between Trump and Ballantine.

The conversion efficiency from AC power to electrons was assumed to be 70%. (Depending on the type of accelerator used, this value can range from 30-90%.) As a result, required input power to the electron accelerator is about 70 kilowatts, which is the value used to determine the capital and operating costs in Table 1.

A 100,000 GPD plant processes about 36.5 million gallons per year. Regardless of solids content, the density of liquid sludge (about 8.4 lb/gal) is little more than that of water. The annual disinfected output can be expressed as 153,000 tons of wet sludge. At 5% solids, this is about 7,500 dry tons treated for a cost of $120,000 or <u>$15.60 per dry ton</u>. For comparison purposes, one 1974 study indicates that it would cost between $23 and $29 a dry ton to pasteurize liquid digested sludge using No. 6 Fuel oil (18).

The capital and operating costs of electron irradiation would be the same for irradiating sludge at concentrations higher than 5%. It is conceivable that economic benefits might result from dewatering the incoming wastes to increase sludge concentrations prior to irradiation. For example, a 5% sludge concentration from a 300,000 GPD treatment plant, if dewatered to achieve a 15% concentration, could be handled by the 100,000 GPD irradiation system at the same total irradiation cost as given in the previous example. However, the cost per dry ton would be only a third as much, or $5.20 per dry ton.

A 100,000 GPD irradiation system produces some 153,000 tons of wet sludge per year. The amounts of dry yield (upon which cost recovery would be based) varies with the concentration of incoming sludge. For example, A 5% concentration of incoming wastes produces dry yield of 7500 tons/yr.

A 20% concentration of incoming wastes, after vacuum filtering and/or centrifuging, produces dry yield of 30,000 tons/yr.

A 60% solids concentration, after centrifuging and composting, has a dry yield of 90,000 tons/yr.

Thus the cost per dry ton is greatly reduced by concentration of solids prior to irradiation. Obviously the increased costs to concentrate must be balanced against the decreased costs of irradiating more concentrated sludge.

It is possible that costs of irradiation may be reduced further by exploiting various synergistic effects. Studies at the Sandia Laboratories in Albuquerque, New Mexico, confirm that the combination of heat and radiation used on sludge reduces the dosage required for disinfection. In addition, MIT has studied the effect of oxygen availability at the time of irradiation as a means of increasing the efficiency of the radiation treatment (19).

4.0 SOME BUSINESS OPPORTUNITIES

If the outcomes of experiments at the Deer Island facility continue favorably, three major thrusts of business opportunities seem imminent:

1. The design, manufacture, and construction of electron irradiation systems and components.
2. The modification, sale, and use of pasteurized sludge for its nutritional value.
3. Research and development efforts to assure low cost, safe, and socially and environmentally acceptable uses of sterilized sludge.

All sewage sludge disposal or utilization programs have been hampered by real or imagined concerns about the pathogen problem. That problem now appears to be solved economically, but social and institutional concerns remain (20). Research and development programs are needed to address those concerns.

We address below opportunities for sale of irradiation systems and components, possible new opportunities in agriculture, and some ideas for aquaculture systems.

4.1 Electron Irradiation Systems and Components. Electron irradiation systems lend themselves to relatively simple commercialization because of several basic properties.

1. The technology is well known, simple, and very reliable. Maintenance should be low.
2. The systems can have modular capacity by paralleling units. Thus, only a few standardized units are needed.

3. The systems operate on standard sixty cycle electrical systems and can be installed anywhere.
4. The process is an in-line continuous one that requires only a single exposure to radiation during flow-through procedure.
5. Electron irradiation is safe and efficient. Because it distributes its disinfecting ionization throughout the volume (as opposed to a surface process) it can treat both solids and liquids with excellent quality control. There need be no concern about continuous efficacy of the process so long as the electrons are being accelerated.

These factors imply the systems can be used on a production basis by municipalities and other user groups.

4.11 Municipal Markets. The dollar size of the maximum municipal market can be roughly estimated from the Deer Island cost example and data on the total volume of sludge handled by the municipal sewage systems of the United States.

The cost of the electron irradiation hardware (i.e., power supplies and electron gun, vacuum chamber, "windows," etc.) is about $300,000 for 50 KW of electron beam power or $6,000 per KW of power.

50 KW of power produces enough radiation power to treat 100,000 gallons per day.* Thus, the price of equipment to treat this water is about $3 for each gallon per day of capacity of digested sewage sludge.

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*The energy conscious reader will note that it takes only 14.4 watt hours/gal. or about 53 BTUs to sterilize a gallon of water. Compare that with the 1251 BTUs needed to raise the temperature from 60° F to 212° F!

Very rough estimates suggest about 100 million gallons per day (1974) of 5% sludge is processed each day in the U.S. (21). This amounts to 1000 times the capacity of the Deer Island facility and 1000 times the cost for irradiation systems. These data imply a total market of some $300 million for high-energy electron accelerators. If we recognize that perhaps only 10% of this total may be appropriate for application of electron irradiation (i.e., alternatives or competing technologies may be more appropriate), the potential U.S. market is about $30 million.

This figure could easily vary by an order of magnitude. The market over a ten year period may be as small as $10 million or as large as $100 million. It is very likely not a billion dollars nor a few million.

4.12 Miscellaneous Systems Applications. The modular nature of electron beam processing systems and their efficient use of conventional electric power make them readily adaptable to special purpose systems.

One class of special purpose systems is the "Marine Sanitation Device" (MSD) that will be required by the U.S. Coast Guard starting in 1977 [(33) Code of Federal Regulations, 159]. One way to meet the requirements (minimum fecal coliform count and no visible floating solids) is a simple holding tank that is pumped out in port or on the high seas. However, this takes up valuable space and is particularly unsuitable for ships with high-density populations operating in coastal or inland waterways. Electron irradiation could sterilize both recycling systems and flow through systems. Irradiation devices are compact, modular, safe, self-contained, require no holding tank, and can be assembled from "off the shelf" components. The practical application has been described by Bebar (22).

A special subset of waste treatment systems could be package or unit waste treatment systems for industrial, institutional, or municipal systems. In some of these, chlorine treatment or ozone treatment may be prohibited or undesirable. The modular nature of the electron irradiation system makes them particularly adaptable to package systems. Examples might include hospital waste disposal systems, disposal systems for large marinas, treatment of waste from food processing plants, and package treatment systems for small municipalities.

4.2 Profitable Utilization of Sewage Sludge. Recycling has long been considered one of many alternatives for sewage sludge management in the U.S. The subject has become of greater interest as legal, social, and environmental constraints have eliminated many alternatives. It is only a slight exaggeration to suggest that federal regulations may preclude all existing alternatives. The quandry that Philadelphia faces is well known. The documentation (23) on this revealing case in point is required reading for an understanding of the dimensions of the disposal problem.

It is perhaps obvious that within twenty to fifty years all sewage sludge will be recycled, just as has been done in animal husbandry and farming over the world for ages. Thus, the basic idea is not new. What is new and interesting and potentially profitable is that electron irradiation provides a means for economically disinfecting sewage sludge in large volumes, thereby making utilization of sludge as a fertilizer acceptable from a health viewpoint.

Several countries in Europe require pasteurization of sludge before it is spread upon the fields. Such "cleaning" appears to enhance public acceptance of the practice. In the U.S., crops grown on sludge fertilized fields generally are restricted to livestock feed only. The USDA recommends at least a three year wait for human consumption of crops from sludge fertilized fields. An argument could be made, following the European example, for human consumption of crops grown from pasteurized sludge. This would open up more land for sludge utilization and might be particularly useful to truck farms close to urban areas. Many more options, such as spreading liquid sludge on highway median strips, are not being used to the extent possible because of a reluctance to expose the public to a potential health hazard.

4.21 Economic Considerations in Sludge-Based Fertilizers. The value of sludge depends upon its content, and content in turn depends upon the source of sludge. The value of sludge today depends upon its value as a plant nutrient in both the agriculture and aquaculture markets.*

The most abundant nutrient values in municipal sludge are:

Nitrogen	1-6%	(2/3 organic, 1/3 inorganic)
Phosphorous	1-2%	
Potassium	.2%	

Plus various micronutrients--i.e., metals in trace concentrations, the most useful being zinc and copper, and the most dangerous being cadmium and mercury (24).

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*There are also, no doubt, protein, carbohydrates, and other animal nutrient values in sludge, but we have been unable to determine the extent of the value, if any. In addition, sludge is an excellent soil "conditioner" as a source of humus.

The largest value of sludge for fertilizer is as a nitrogen source. Assuming 5% nitrogen in dry sludge and a market price of $220 per ton for nitrogen, the value of the nitrogen content is $11.00 per dry ton of sludge. As noted on page 11, the cost of irradiation is dependent on the concentration of the solids in the sludge ($15.60 for 5% solids).

Two comments should be made at this point before concluding that the value of the sludge can be made to equal costs. First, the output of the irradiation process is not dry solids, it is a wet (sterilized) slurry. Transportation costs for moving the material will be high and the value may be significantly lower because of the low concentration of nitrogen in the solids and the low concentration of solids in the slurry. Clearly there are trade-offs involved in determining how much additional processing to increase concentration must be carried out. The cost of centrifuging, for example, would have to be offset by decreased transportation and processing costs--per unit of nitrogen. Nevertheless, the use of liquids as fertilizers is practiced worldwide and the assured sterilization by electron irradiation may make this practice acceptable, widespread, and profitable in the U.S.

Second, it should be noted that the $220/ton value of nitrogen may not be an appropriate index of the value of processed sludge as a nutrient and soil conditioner. For example, Milorganite, a dry fertilizer made from processed sewage in Milwaukee, sells for $80 a dry ton (25). A similar compound, Hou-Actinite, is being processed from Houston's sewage and sold wholesale to a broker for approximately $25 a dry ton (26). The difference in price is somewhat a function of content, but mainly reflects the differences in marketing approach--Milwaukee is a retailer, while Houston is a wholesaler.

The processing, pasteurizing, and drying costs range around \$100 to \$150 per dry ton of output and appear to be increasing as the cost of fuel rises. Thus, processing and selling sludge in a dry form appears to be only marginally profitable at best and should be considered a procedure for minimizing costs of disposal, not for maximizing profit.

4.3 A Sludge Based Aquaculture System. The use of sterilized sewage sludge as a source of nutrients for the culture of aquatic organisms has interesting potential for the recycling of nutrient components of wastes (27,28). The chemical and biological pathways for this conversion are reasonably well understood and have been elucidated in a vast body of scientific literature (29).

Given that the irradiation treatment of sewage sludge produces a nutrient-rich, sterile medium for the culture of microorganisms, a controlled ecosystem could be designed using this nutrient energy base upon which to structure a food web capable of supporting the commercial production of marketable human or animal foods. Such a contrived ecosystem might be managed intensively to achieve high efficiency of production of desired high-value aquatic species. Alternatively, extensive culture systems based on irradiated sludge might be managed to produce large quantities of animal feed composed essentially of algal or fungal single-cell proteins (31).

In either case the influent must satisfy certain technical and social principles, such as the criteria for an appropriate nutrient balance, freedom from toxicity to the culture environment, and compliance with public health regulations relating to pathogens, heavy metals, and radioactivity. In the case of human food, certain cultural and aesthetic values are also important considerations.

The demonstration that "controlled eutrohication" of an aquacultural system can support high densities of planktons has been well documented by Dr. John Ryther and his co-workers at Woods Hole Oceanographic Institution (31). The experiemental work has been performed with secondary treated sewage effluent diluted with seawater and used as a nutrient medium for the culture of marine phytoplankton and algae.

Unicellular marine algae can be produced in very high densities--almost a slurry--more than a million cells per milliliter. This large biomass is a consequence of the ability of plant cells to feed themselves by photosynthesis. An algal culture is a solar energy collector and food energy storage system, which is dependent upon the availability of certain mineral nutrients such as nitrogen, phosphorous, potassium, calcium, iron, etc. These nutrients are contained in partially digested sewage in the form of nitrates, ammonia, phosphates, and other salts. Modification and removal of these nutrients from the wastewater by algae and other planktonic microorganisms acts, in effect, as a biological tertiary sewage treatment. Under appropriate management, such treatment can clean up the water sufficiently to enable it to be safely reintroduced into the environment. Most of the nutrients have been locked up temporarily in the algal cells.

However, the recovery of the algal cells by physical means, such as centrifugation, filtration, or flocculation has proven to be uneconomical compared to competing high protein sources, such as fish meal or soybeans. On the other hand, certain filter feeding aquatic animals that have high value as human foods, such as several bivalve molluscs (oysters, clams, scallops, mussels), can feed on the algal cells and the other aquatic microorganism suspended in the culture. A very considerable portion of the plankton population can thus be filtered out of the culture, locking up in the form of valuable mollusc meats the nutrients that had their origin in the wastewaters.

The dissolved nutrients that are not taken up by the plankton, and those that reenter the culture from the excrement of the shellfish, may be subsequently removed from the system by the culture of the macrophytic algae. These seaweeds have very considerable commercial value as a source of phycocolloids (32).

Several other polyculture systems based on different food pyramids can be devised utilizing wastewater nutrients. As before, one must start at the base of the food chains with the autotrophic, photosynthetic organisms (algae). However, following the algal culture, numerous herbivorous aquatic marine animals, which are important human food resources in lesser developed societies, can be chosen. Examples are the milkfish, mullets, and numerous reef fishes, all of which forage on both the planktonic and benthic algae that thrive when fertilized on the nutrient coming from a wastewater treatment facility. In fact, aquaculture, as it is practiced in much of Southeast Asia and in Africa, is highly dependent on the insertion of manures, both animal and human, as a primary source of fertility to sustain the productivity of the system. There are unacceptable public health hazards associated with this practice which electron irradiation would avoid.

Another attribute to be realized by a culture system designed to use the irradiated sludge effluent of a wastewater treatment plant is the considerable flow rate of the fluids through the system. Since the cost of pumping is now borne by the sewage treatment process, presumably the culture system at the end of the process stream receives the delivery of its raw materials at little or no sharing of the pumping burden. Although a dwell-time will be required in the culture system to allow for a phytoplankton bloom to develop, one would expect to design for a flux-equilibrium to establish a continuous culture system. Even though the retention of the culture medium in ponds or tanks may be for several days, the cost of movement in and out may be minimal.

An aquafarming venture employing some of the technology summarized above may generate a very considerable volume of high-value human foods and animal feed components. In addition, the tertiary treatment of sewage by the operation of polyculture aquafarms may be advocated on the basis of the benefits to be derived from pollution abatement and environmental protection alone. Under such motivation, an aquafarm might be judged to be cost effective if only self sustainability or break-even is achieved.

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