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Recent Developments in the Sandia Laboratories' Sewage Sludge Irradiation Program

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RECENT DEVELOPMENTS IN THE SANDIA LABORATORIES' SEWAGE SLUDGE IRRADIATION PROGRAM

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ABSTRACT

Pathogen reduction studies have shown that a 1 Mrad treatment (or less at elevated temperatures) is very effective in eliminating pathogenic bacteria and viable parasite ova in liquid sludges. Heat is effective in reducing levels not only of pathogenic bacteria and Ascaris ova, but viruses as well. Ammonia has been shown to be virucidal to poliovirus and several other enteric viruses.

Sludge processing costs are seen to be marginally competitive with heat treatment for liquid sludges and relatively economical for composted or dried sludges.

Physical/chemical effects studies have shown that the effects of irradiation of sludges on dewatering properties are not significant when compared to polymers, nor is the combined effect synergistic.

Dried, irradiated undigested sludge has been shown to be of significant nutritional value when used as a feed supplement for sheep and cattle, as well as in agronomic uses. No significant harmful effects have been demonstrated in the feeding program thus far.

Product enhancement studies are currently under way, including schemes for removing nitrogen from effluent streams for addition as ammonium salts to sludges.

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RECENT DEVELOPMENTS IN THE SANDIA LABORATORIES' SEWAGE SLUDGE IRRADIATION PROGRAM

Introduction

The Sandia Laboratories' Beneficial Uses Program is a joint Energy Research and Development Administration/Environmental Protection Agency effort whose objective is to utilize beneficially the nuclear waste isotope cesium-137 and the rapidly increasing amounts of sewage sludge being generated as we clean up our wastewater discharges. The isotope is used to irradiate the sludge to reduce pathogens so that the sludge can be used effectively in unlimited agricultural applications.[1] Studies[2] under way indicate that social, economic, public health, and technical pressures are resulting in searches for better methods of disposal or utilization which are less polluting, energy and resource conservative, and which recognize recycling as a matter of great importance in a food-hungry world.

Although much of the work reported here has been done in liquid sludges, the emphasis in the Sandia research program has shifted in the past year and will continue to emphasize the treatment of dried sludges. Research in pathogen reduction and utilization of composted sludges, dried raw sludges, and dried digested sludges has become interesting for the following reasons.

Treatment System Economies

Treatment for pathogen reduction can be significantly more economical when a large amount of the water has been removed. Heat treatment and irradiation costs are both reduced by not treating the excess water in normal sludges.

Pathogen Regrowth and Odor Control

Dried sludges do not suffer from the bacterial regrowth problem associated with liquid systems. The dryness inhibits regrowth and has a pronounced beneficial effect on odor control.

Land Use Barriers

Dried or composted sludges are generally more easily applied to the land over longer portions of the year. Wet application systems, due to increased weight among other reasons, need favorable soil conditions for application. Dried sludges can be more easily stored pending favorable application conditions.

Social Acceptability

Dried or composted sludges tend to be more socially acceptable than wet municipal sludges. The social stigmata of sludge utilization have been demonstrated to decrease significantly when the material has been dried (Milorganite and Actinite).

Utilization Potential

Dried or composted sludges are potentially more useful in terms of specialty products, such as bagged formulations, meeting the various users' specific needs. For this reason, the dry product commands a higher market price.

Transportation Costs

Utilization or disposal are both adversely affected by the transport costs of the water in sludges. Reductions of this cost by at least 50 percent can be achieved by drying or composting. Energy conservation is an important aspect of this consideration.

Technological Advances

The advances in composting technology such as at the U. S. Department of Agriculture, Beltsville, MD, and the Los Angeles District, Los Angeles, CA, make composting a very promising treatment option. Similar advances in centrifuge and filter-press technology will increase solids content leading to faster drying and lowered handling costs for the sludge feedstock for treatment processes.

Energy Conservation

Energy conservation is achieved not only in reduced transportation needs but in any treatment processes used. Incineration is hard to justify if a suitable land application option can be devised using less energy-intensive treatment processes. Dried or composted sludges could provide a significant amount of the agricultural nitrogen requirements, thereby conserving up to two percent of the annual national natural gas used.

Pollution Control

Land utilization of dried or composted sludges versus incineration or ocean dumping could favorably impact the decrement in air quality due to incineration or the pollution of our offshore waters due to ocean dumping.

Viable Disposal Options

The closing off of some disposal options being mandated by law, such as cessation of ocean dumping by 1981, is causing cities to search for reasonable alternatives. Composting is being considered by some major metropolitan areas as the most reasonable option at this time. When this option is implemented, a large amount of compost will need disposal and treatment for land application is one of the obvious solutions.

Raw sludges, dried and treated for pathogen and odor control, offer an additional potential of sufficient value to merit consideration and study. These sludges, as noted elsewhere in this report, have twice the nitrogen and energy content of digested sludges. In terms of land application for agronomic value or animal refeeding for feedstuff value, their enhanced potential make them a more desirable end product of the municipal waste management system. Their increased value could favorably impact the disposal options of most metropolitan areas.

This report will review briefly the recent pathogen reduction work, the sludge processing costs work being done to support a Cost/Benefit study, the agronomics and animal refeeding studies, the work in product enhancement and physical/chemical effects, and, lastly, a status report on the dried sludge irradiator being built to develop the design and treatment parameters for a demonstration plant to be built in the future in conjunction with a large city's composting or air drying operation.

Pathogen Reduction Studies

Bacteriology--The major impetus for irradiation treatment of sewage sludge is reduction in pathogens. An important aspect of this program is elimination of those bacteria classified as such.

Rates for bacterial inactivation by ionizing radiation are normally given in terms of "D-value," i.e., dose required to effect a 90 percent reduction in population. Figure 1, for example, shows an inactivation curve for *Salmonella enteritidis* serotype Montevideo in composted sludge.[3] The "D-value" is approximately 30 kilorads/log. Results of similar determinations for liquid digested sludge are summarized in Table I.[4] The numbers in parentheses are D-values determined for oxygenated sludge (oxygen was bubbled through the samples prior to and during the irradiation). It can be seen that oxygenation significantly reduces the absorbed dose required for a given decrease in population of these bacteria, even at elevated temperatures. Another conclusion of these studies is that most of the enhancement at elevated temperatures is due to the effect of heat, not to synergistic behavior.

Radiation treatment of composted sludge is a more attractive proposal from an economic standpoint since most of the water has been eliminated. Besides the data in Figure 1, no inactivation rate parameters have been defined for irradiation of bacteria in compost. Several experiments have been conducted on heat inactivation of bacteria in composted sludge.[5] Figure 2 shows the effect of heat treatment on fecal streptococcus bacteria in compost. As has been reported,[6] these bacteria are among the "hardiest" in sludge in terms of radiation and heat resistance. Coliforms and salmonellas exhibit much greater heat sensitivity than do fecal strep (see Figure 3).[5]

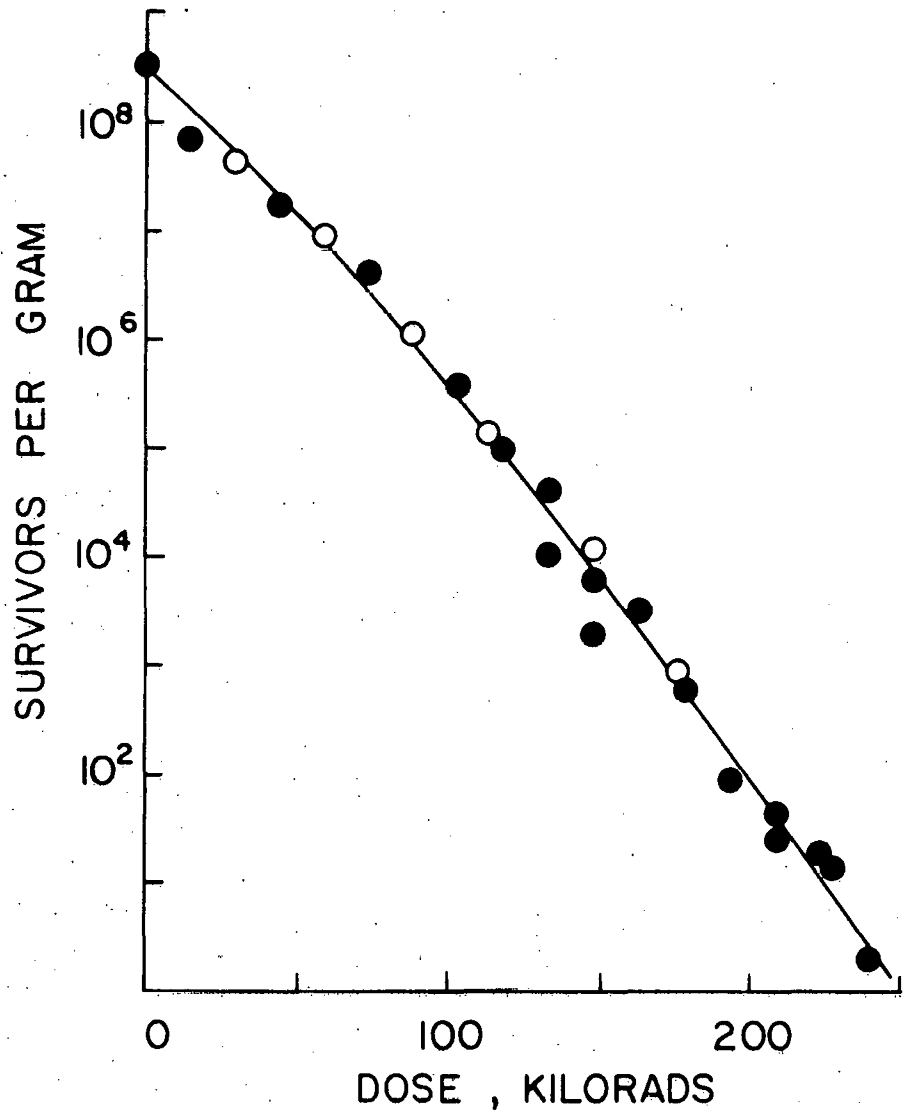

Figure 1. Radiation inactivation of Salmonella enteritidis ser. Montevideo grown in composted sewage sludge.

Table I

D-values for bacterial inactivation. The effect of oxygen on D-values is indicated by the numbers in parentheses.

Temperature, °C	Coliforms	Salmonella	Fecal Strep
23	25-30 (8)	26 (13)	130-135 (87)
40	25		129
50	23	19 (11)	109
55	10-15 (4)		86
60	15		70-97 (32)
65	5		46

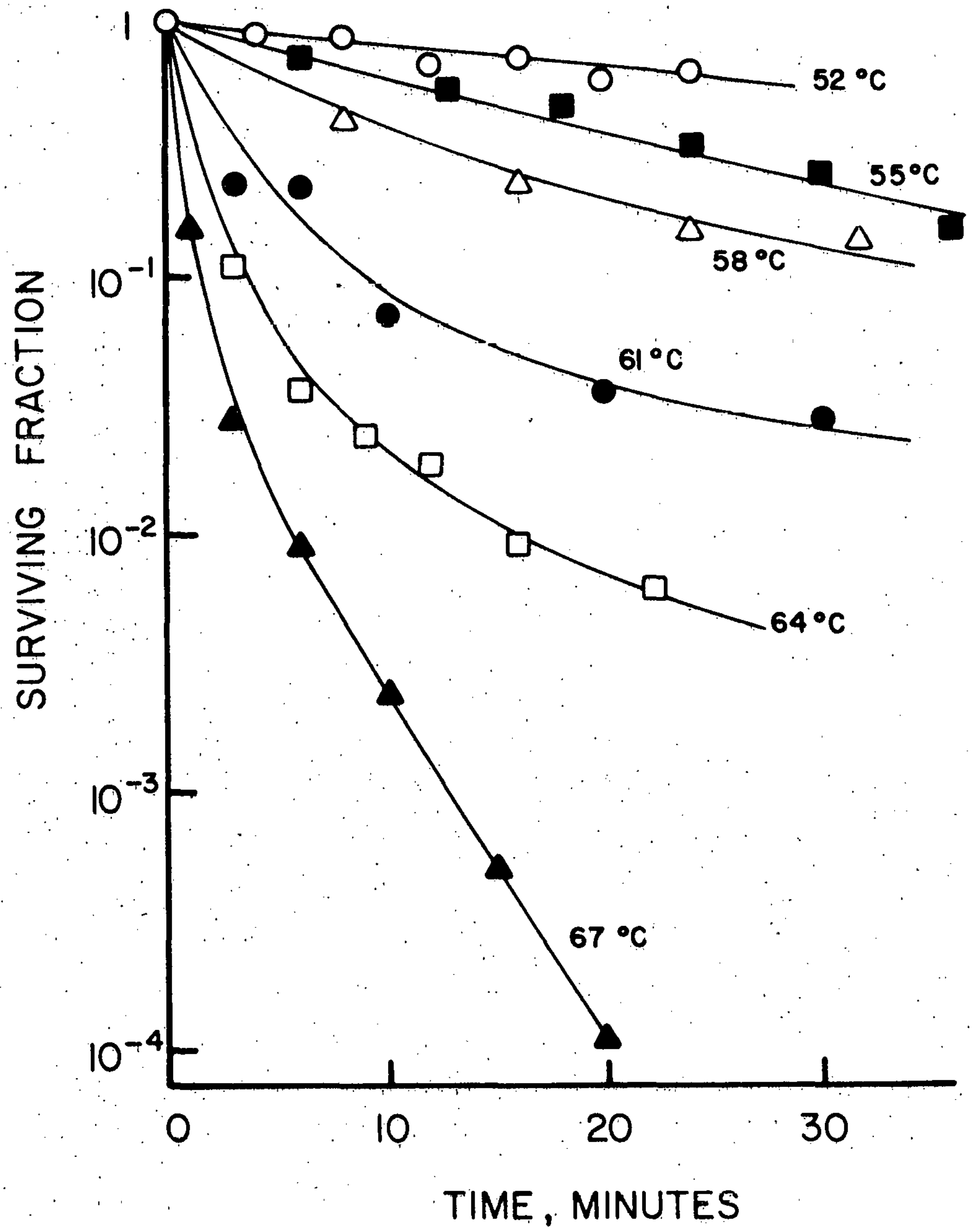

Figure 2. Heat inactivation of fecal streptococcus bacteria in composted sludge at 52 C (○), 55 C (■), 58 C (△), 61 C (●), 64 C (□), and 67 C (▲).

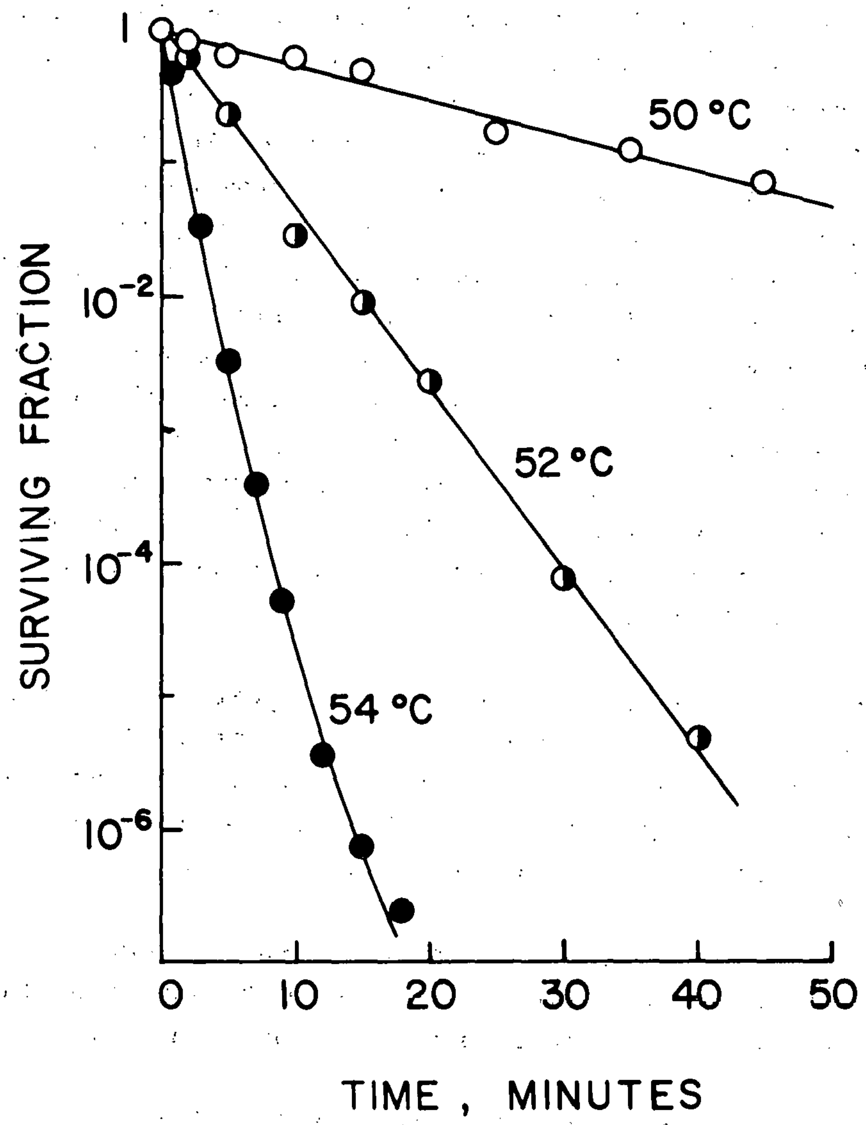

Figure 3. Heat inactivation of Salmonella enteritidis ser. Montevideo in composted raw sludge.

Under the proper conditions, especially if the bacterial population of sludge (liquid or composted) is reduced to low levels, recontamination with untreated material can lead to serious problems through growth of pathogenic bacteria to high levels. Figure 4 shows that either coliforms or fecal strep bacteria (typically non-pathogenic) grow rapidly in sterile sludge inoculated to an "initial population of 10 bacteria/g.[4] There is evidence that salmonellas grow rapidly as well, both in composted sludge[7] and in liquid sludge. Figure 5 shows the growth of fecal strep in composted sludge under various conditions. It is seen that the bacteria grow best when the sludge has a low initial bacterial population, but that even in a system saturated with salmonellas (mixed culture) they grow rapidly to fairly high levels. In normal compost, where the bacterial population is large, there appears to be an increase, followed by a slow decline in fecal strep population. This is in agreement with observations made on salmonellas in compost.[8] It is important to note that radiation treatment, which reduces the bacterial population drastically, may lead to a more severe regrowth problem than no treatment at all. Research is currently in progress on inhibition of growth in sludges by competitor microorganisms.

Parasitology--Inactivation data for *Ascaris lumbricoides* ova under various irradiation conditions are summarized in Table II. It is clear that any treatment (at least in liquid systems) which is sufficient to eliminate pathogenic bacteria will be satisfactory for prevention of embryonation in these parasite ova.

Heat alone is very effective in preventing embryonation.[9] Figure 6 shows reduction in embryonation ratio by treatment at various temperatures of aqueous suspensions of *A. lumbricoides* ova.

Experiments are currently under way to determine inactivation parameters for parasite ova in composted sludge.

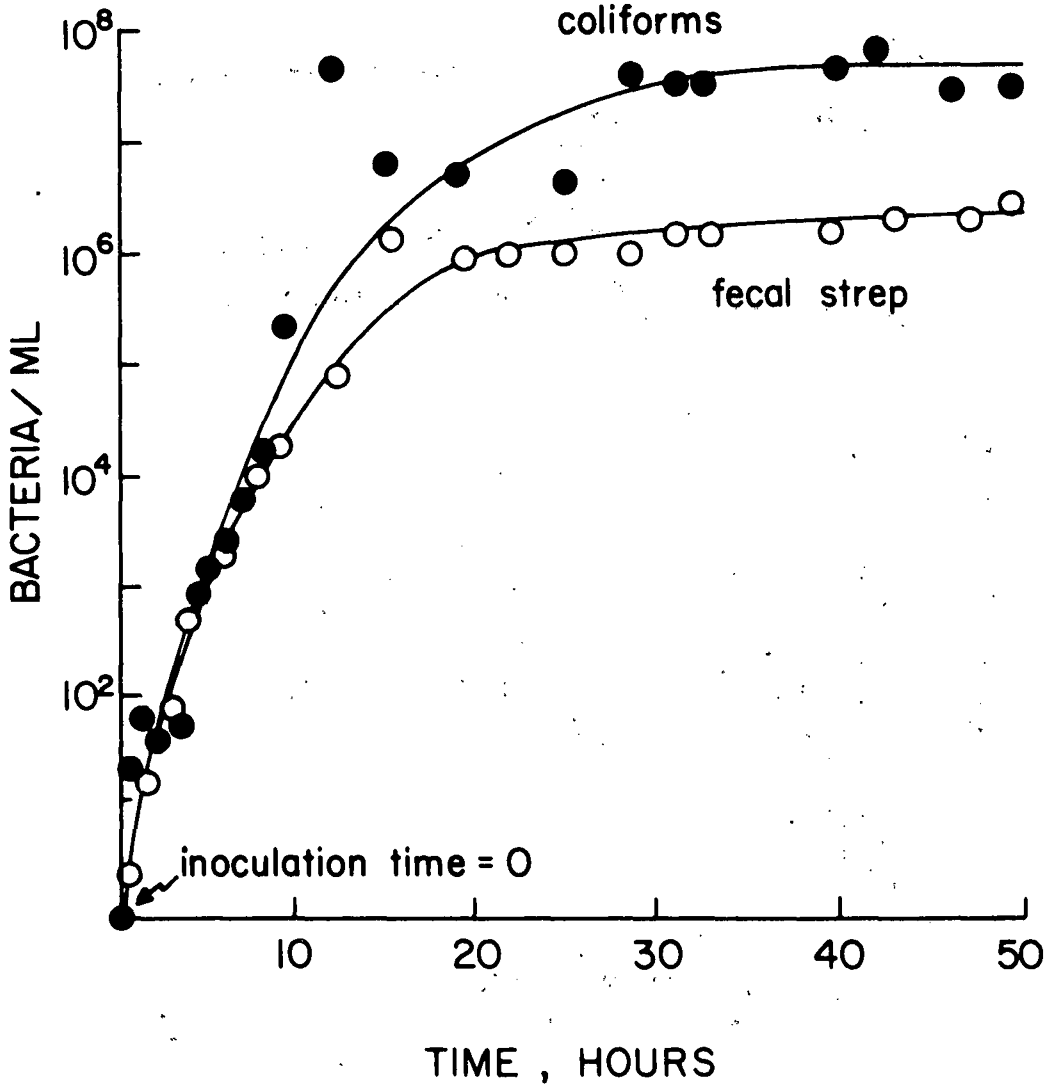

Figure 4. Growth of coliform (●) and fecal streptococcus (O) bacteria in sterile liquid digested sludge (35 C).

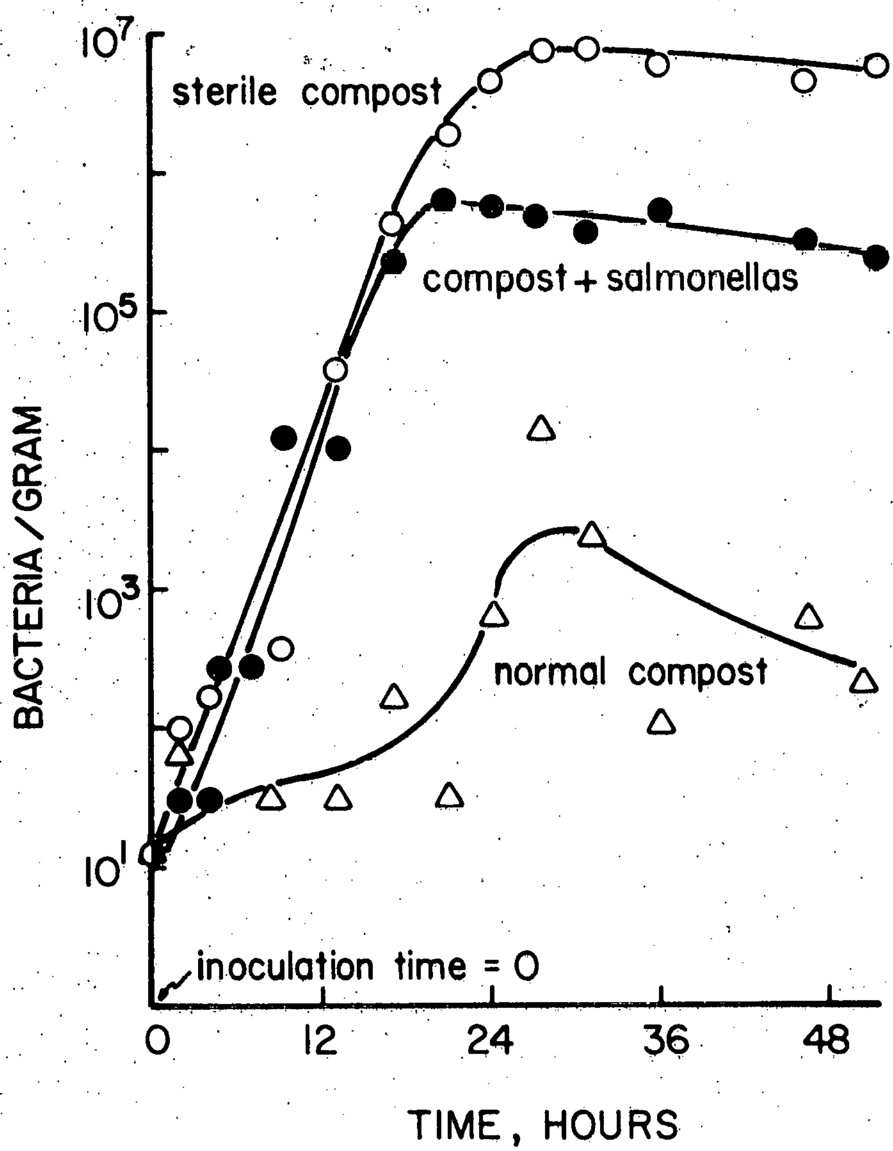

Figure 5. Growth of fecal streptococcus bacteria in normal composted sludge (△), in sterilized composted sludge (O), and in composted sludge saturated with Salmonella spp. (●). In the last case, following sterilization of the compost, Salmonella spp. were allowed to grow to approximately 10^8 bacteria per gram.

Table II

Inactivation of *Ascaris lumbricoides* ova

IRRADIATION TEMPERATURE (°C)	INACTIVATION MEDIUM	DOSE FOR 3-LOG REDUCTION (KRADS)
23	SLUDGE	90
23	SALINE	65
23	WATER	85, 140
23	SUPERNATANT	140
47	WATER	40
51	WATER	40
51	SUPERNATANT	70
60	WATER	10

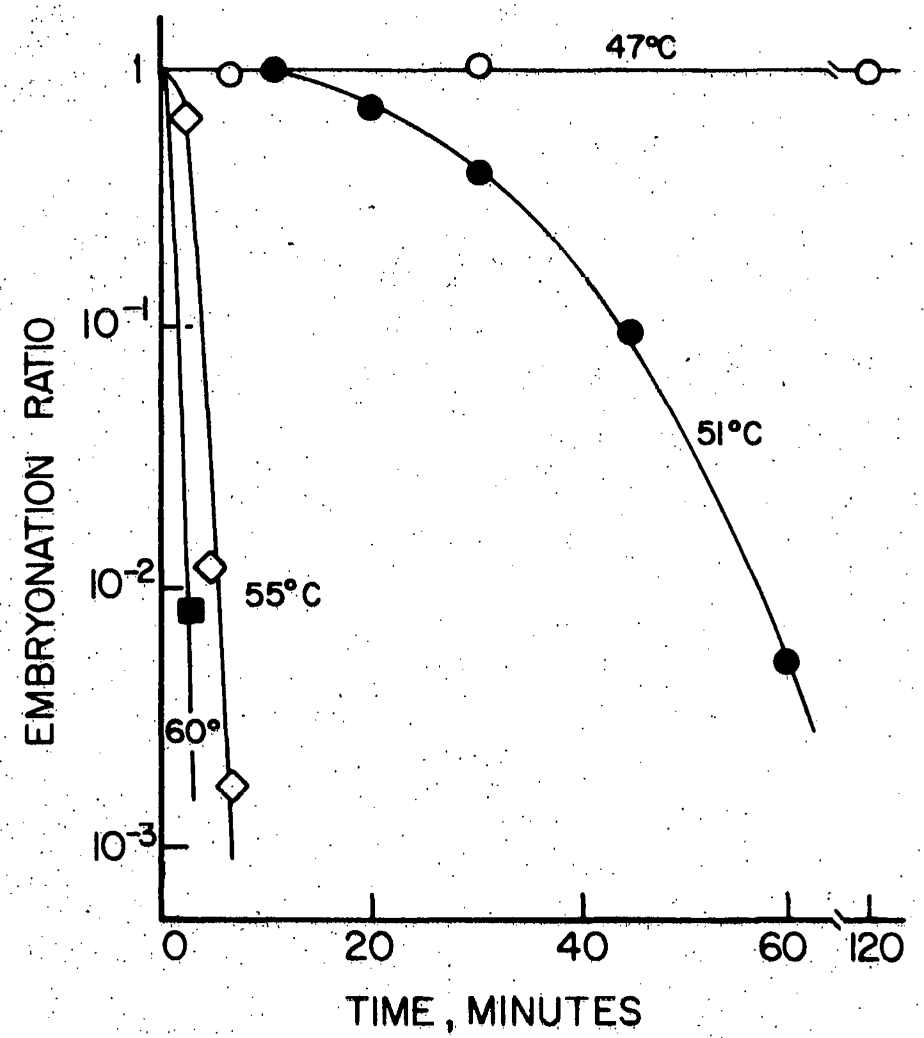

Figure 6. Heat inactivation of Ascaris lumbricoides ova.

Virology--Methods are being researched to rid wastewater sludge of infectious enteric viruses at low-cost without reducing the economic value of the sludge. The experimental procedure used for this study is to seed sludge with large numbers of infectious viruses, and to determine the effects of various treatments on the recovery of viral plaque-forming units. The recovery of viral particles and the physical effect of the treatments on these particles is monitored by using purified, radioactively-labeled viruses.

In initial experiments performed to determine the effects of anaerobic digestion on poliovirus, the rate of viral inactivation was compared in raw and digested sludge. It was found that digested but not raw sludge contained virucidal activity (Table III).[10] Further analysis revealed that the virucidal agent is ammonia which inactivates poliovirus in its uncharged form but not as ammonium ion.[11] The pK for the conversion of ammonium ion into ammonia is 9.2. Digested sludge was found to be virucidal because its pH after removal from the digester is typically greater than 7.5. On the other hand, raw sludge was not virucidal because its natural pH is about 6, a pH at which essentially all ammonia is present as non-virucidal ammonium ion.

In subsequent experiments, it was found that other enteroviruses besides poliovirus were also sensitive to ammonia (Table IV). Reovirus, an enteric virus of a different group, was found to be resistant. Studies are in progress to determine the reason for these differences.

The effect of sludge on the rates of enteric virus inactivation by heat, ionizing radiation and thermoradiation (simultaneous application of heat and radiation) are also being studied. Raw sludge was found to be somewhat protective of poliovirus against radiation and very protective against inactivation by heat (Figure 7).[12] However, when the treatments are applied simultaneously, the rate of virus inactivation is greater than the additive effects of the two individual treatments. This is especially true at low concentrations of sludge.

Heat inactivation of poliovirus occurs much more rapidly in anaerobically digested than in raw sludge (Figure 8).[13] Both types

Table III

Recovery of poliovirus from seeded sludge as a function of incubation time

Incubation Time/ Temperature	Recovery (%) of Plaque-forming Units		
	No Sludge	Raw Sludge	Digested Sludge
15 min, 20 C	100	100	74
5 days, 4 C	100	100	3.8
5 days, 20 C	90	87	0.0027

Table IV

Effect of ammonia on infectivities of several strains of enteric viruses[a]

Virus	PBS	Percent Recovery of pfu		
		Tris, pH 9.5	NH_4Cl, pH 7	NH_4Cl, pH 9.5
poliovirus type-1 strain CHAT	103	63	53	<0.000035
poliovirus type-1 strain Mahoney	108	100	68	<0.000014
poliovirus type-2 strain 712	86	60	24	<0.000044
coxsackievirus A13	58	28	35	<0.00012
coxsackievirus B1	107	100	52	<0.000046
echovirus 11	61	9.6	34	<0.00015
mengovirus	84	100	17	<0.000026
reovirus type-3	55	9.8	62	3.1

[a]Virus was diluted 10-fold into phosphate-buffered saline (PBS), pH 7.0, 0.1 M Tris (hydroxymethylaminomethane (Tris), pH 9.5, 0.1 M Tris-0.5 M NH_4Cl, pH 7.0, or 0.1 M Tris-0.5 M NH_4Cl, pH 9.5, and incubated at 21 C for 24 h. The final pH values of the samples were then determined and each sample was titered after sonication in 0.1 percent sodium dodecyl sulfate. Percent recoveries were determined relative to a control sample left frozen during the period of incubation.

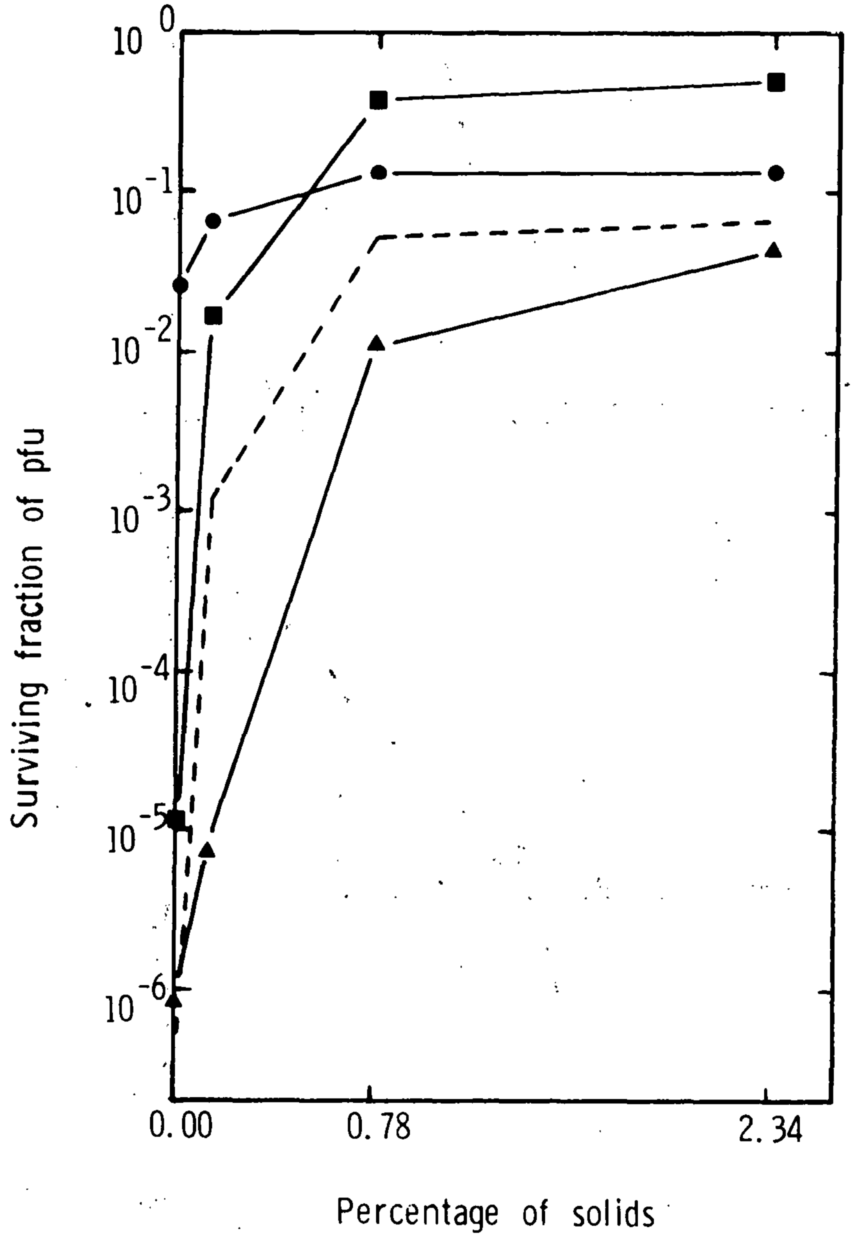

Figure 7. Effect of sludge on poliovirus inactivation by thermoradiation. Samples of virus in sludge containing the specified percentage of solids were either irradiated (dose rate: 30 krads/min) for 10 min at 20 C (●), heated for 10 min at 47 C (■), or irradiated for this same period of time at 47 C (▲). The samples were then assayed for infectious virus. The dashed line is the additive effects of heat and radiation given individually.

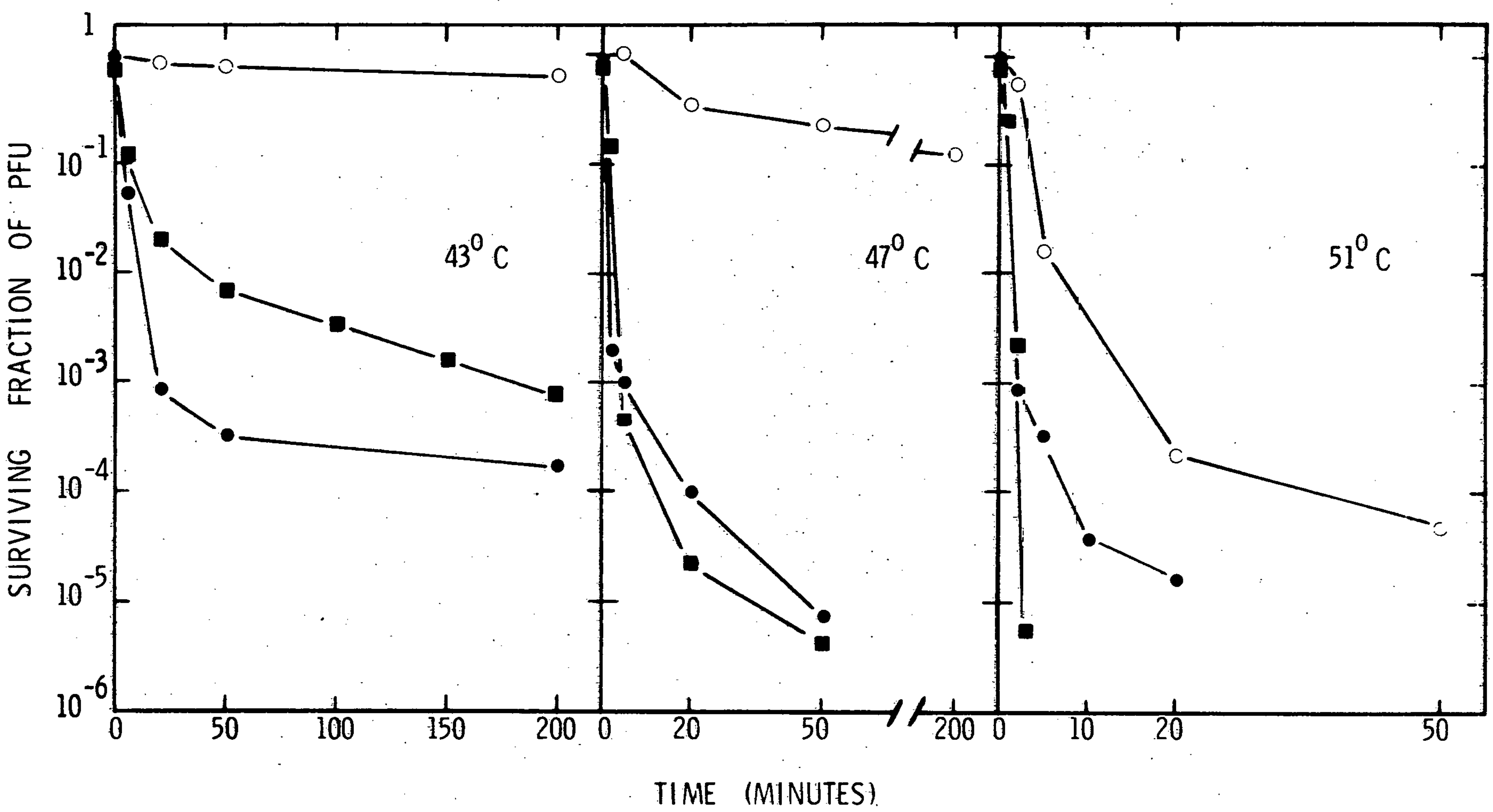

Figure 8. Effect of sludge on the rate of heat inactivation of poliovirus. After a 10-fold dilution into buffer (PBS), raw sludge, or anaerobically digested sludge, poliovirus was mixed for 15 min at room temperature and heated at the specified temperature. Samples were removed from the incubation bath at the times shown and immediately cooled in ice. After sonication in 0.1 percent SDS, each sample was directly assayed for total plaque-forming units on HeLa cells. Symbols: (O) raw sludge; (■) digested sludge; (●) PBS.

of sludge contain material that protects poliovirus against heat, but this protection is overcome at the higher pH values of digested sludge by indigenous ammonia.[14,15] Because the protective material in sludge is non-volatile, it becomes concentrated during drying. As a result, the rate of heat inactivation of poliovirus occurs much more slowly in dried than in wet raw sludge (Table V).[5]

Although ammonia is not virucidal for reovirus,[11] a common enteric virus with different chemical and physical properties than poliovirus, wastewater sludge contains another agent that significantly lowers the temperature required to inactivate reovirus.[15] This uncharacterized material causes accelerated heat inactivation of reovirus at temperatures at least as low as 30 C (Figure 9). Because this agent is also activated by an increase in pH as is ammonia, it should be possible to eliminate two of the most numerous enteric viruses in sludge at moderate temperatures by simply increasing the pH.

In another series of experiments, the effect of dewatering on the inactivation rates of enteric viruses in sludge was determined.[16] For this study, water was evaporated from seeded raw sludge at 21 C, and the loss of viral plaque-forming units was measured. Initial results with poliovirus showed that recoverable infectivity gradually decreased with the loss of water until the solids content reached about 65 percent (Table VI). When the solids content was increased from 65 to 83 percent, a further, more dramatic decrease in virus titer of greater than 3 logs was observed. This loss of infectivity was due to irreversible inactivation of poliovirus because viral particles were found to have released their RNA molecules which were extensively degraded. Viral inactivation in these experiments may have been at least partially caused by the evaporation process itself because similar effects on poliovirus particles were observed in distilled water after only partial loss of water by evaporation (Table VII). Coxsackievirus and reovirus were also found to be inactivated in sludge under comparable conditions (Table VIII) which suggest that dewatering by evaporation may be a feasible method of inactivating all enteric viruses in sludge.

It is hoped that one or more of the treatments examined herein to eliminate infectious enteric viruses from wastewater sludge will be applicable to the procedures already employed during the processing,

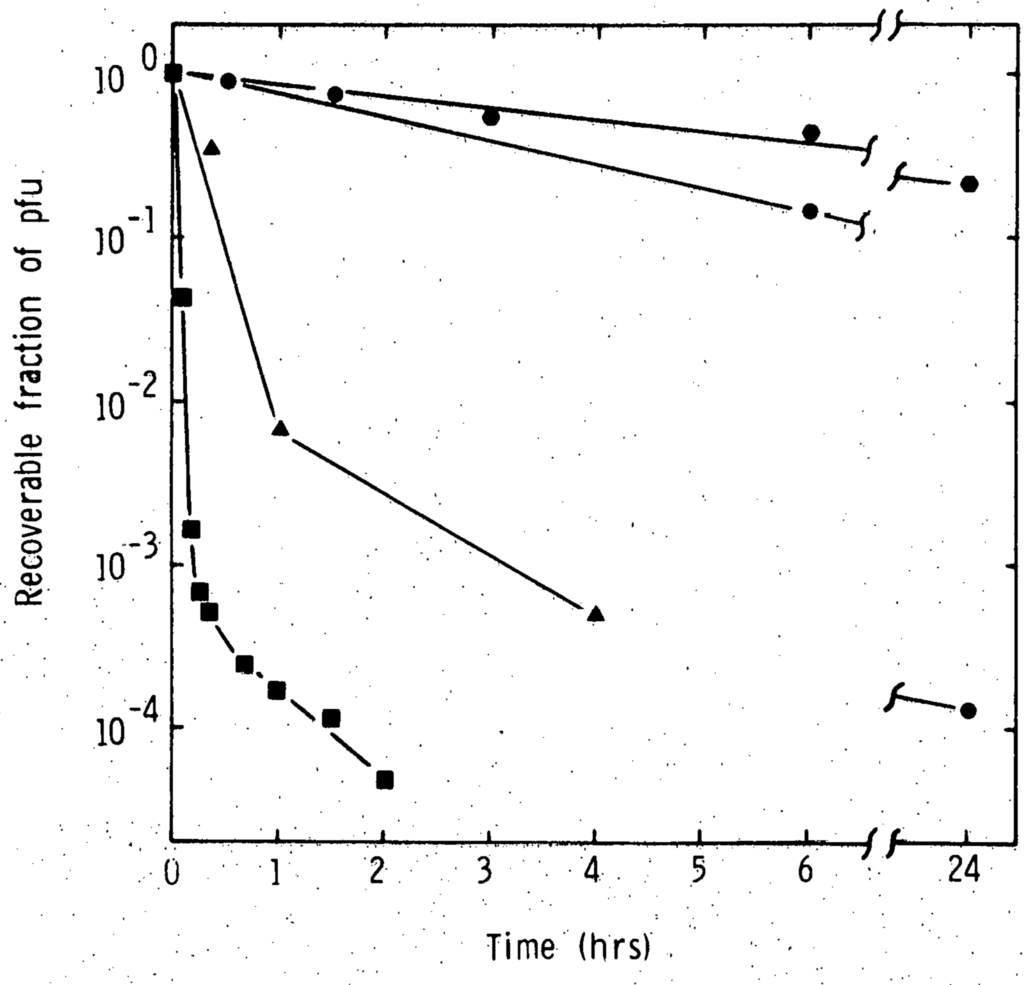

Figure 9. Inactivation of reovirus by processed digested sludge as a function of time and temperature. Processed samples of digested sludge were heated at the temperatures and for the times specified at pH 8.5. All samples were then assayed for plaque-forming units. Symbols: 30 C (●); 35 C (●); 40 C (▲); 45 C (■).

Table V

Heat inactivation of poliovirus in raw sludge as a function of moisture content

Sample	Percentage (%) Recovery of pfu after 20 minutes at 47 C
PBS	0.05
5% Solids	0.3
40% Solids	29
80% Solids	78

Table VI

Recovery of poliovirus plaque-forming units from sludge after dewatering[a]

Final Percentage of Sludge Solids	Recovery of pfu/ml	
	Four Days	Eleven Days
5	1.8×10^7	6.5×10^6
12	1.7×10^7	4.5×10^6
20	9.5×10^6	4.0×10^6
30	6.4×10^6	3.8×10^6
58	5.5×10^6	3.2×10^6
65	4.0×10^6	3.2×10^6
83	2.5×10^3	$<2.5 \times 10^2$
91	1.0×10^3	$<2.5 \times 10^2$

[a]Raw sludge containing five percent solids was seeded with poliovirus and dewatered at 21 C by evaporation to the percentages of solids specified. All samples were kept at 21 C and assayed for plaque-forming units at 4 and 11 days after the time evaporation was initiated. The original titer of the virus in sludge was 2.4×10^7 pfu/ml and this value remained constant in a sample held at 4 C during the 11 days of the experiment.

Table VII

Effect of evaporation on the specific infectivity of [^3H]-uridine-labeled poliovirus[a]

Percentage of Water Removed by Evaporation	Specific Infectivity[b]	Percentage Reduction Relative to Controls
0	1.4×10^3	--
21	7.5×10^2	30
43	7.1×10^2	24
67	6.3×10^2	57
94	6.6×10^1	91
100	1.1×10^{-2}	99.998

[a]Purified poliovirus labeled with [^3H]-uridine was diluted with distilled water and the radioactivity and plaque-forming units recoverable after the evaporation of the specified percentages of water at 21 C were determined. The percentage reduction in the specific infectivity of each sample was then measured relative to a control held at 21 C for the same period of time without loss of water.

[b]Specific infectivity; plaque-forming units per counts per minute of [^3H]-uridine.

Table VIII

Effect of dewatering on the recoveries of coxsackievirus and reovirus from sludge[a]

Final Percentage of Sludge Solids	Recovery of pfu/ml	
	Four Days	Eleven Days
coxsackievirus B1		
5	1.5×10^7	1.3×10^7
33	1.1×10^7	3×10^6
93	1×10^3	$<2 \times 10^2$
reovirus		
5	2.1×10^6	1.2×10^6
20	1.8×10^6	8.6×10^5
40	1.2×10^6	7.0×10^5
60	7.1×10^5	2.3×10^5
73	4.5×10^5	2.0×10^4
94	$<2 \times 10^2$	$<2 \times 10^2$

[a]Samples were treated as described in Table 4. The original titer of coxsackievirus was 1.7×10^7 and that of reovirus was 2.3×10^6 pfu/ml.

disposal and utilization of sludge. Experiments are being planned which will determine the effects of many of these treatments when given in combination.

Sludge Processing Costs

The task of comparing process costs is difficult when the pathogen-reducing ability of each process differs drastically in each different type of pathogen. Many normally used or potentially useful sewage treatment processes, such as anaerobic digestion, anaerobic thermophilic digestion, pyrolysis, incineration, or lime stabilization, affect only certain classes of pathogens. The primary purpose of these processes is not pathogen reduction; and generally, the reduction is accomplished only incidentally. The decision of whether or not the cost of systems such as pyrolysis or incineration will be borne is usually based on improved dewatering properties of the sludge or providing a method for its disposal. In addition, there is the possibility and/or the desirability of connecting two of these unit processes, such as composting and irradiation, in tandem to provide a more uniform, marketable product.

The costs compared here are costs of disinfection processes that are, in a sense, comparable in effectiveness. Although data on the pathogen-reducing ability of many unit processes is in many cases uncertain or unknown, what is known about the effectiveness of thermal pasteurization, irradiation, and the simultaneous application of heat and radiation (thermoradiation) under process parameters defined later is summarized in Table IX from data provided by Brandon[4] and Ward.[17]

The data, to date, for moist thermal and for radiation processes of moist sludges, such as filter press cake or static pile composting, are very similar to that shown in Table IX.

The design criteria and assumptions used to develop the cost estimates used in this section are listed below:

Labor - $10 per man-hour
Electrical power - $0.04 per KWh
Fuel - $2 per million Btu

Table IX

Effectiveness of various treatments on organisms present in liquid sewage sludges

	Number Log Reduction		
	Thermal Pasteurization	Irradiation	Thermoradiation
Fecal Coliforms	>15	>15	>15
Salmonellas	>15	>15	>15
Ascaris Ova	>15	>15	>15
Fecal Strep	>15	>10	> 7
Polio Virus	>15	> 2	> 9

Source Interest Rate - 0 percent and 7 percent amortized over 20 yrs

Solids in sludge stream - 4.5 percent

It should be noted that changing some of the above parameters will significantly alter the economic desirability of the treatment processes. For example, if fuel costs are $4 per million Btu, then at 0 percent interest irradiation becomes significantly less expensive than thermoradiation. At $2 per million Btu, the reverse is true for larger plants. Intermediate data is provided in Tables X and XI and may be used to investigate the effects of different labor, electrical and fuel unit costs.

Liquid Sludge Processing Costs--

1. Heat Pasteurization

Sludge pasteurization costs were developed by Culp/Wesner/Culp and reviewed by Battelle-Pacific Northwest Laboratories. Data was developed for raw and digested sludge with and without heat recovery. However, only the costs for raw sludge without heat recovery are presented here. The following assumptions apply to the development of this data:

Specific heat of sludge = 1.0 Btu/lb/F
Feed sludge temperature = 63 F (17 C)
Heat loss in system = 10 percent

The pasteurization plan design provides for two reactors to enable a more continuous operation. An allowance for storing a four-day volume of pasteurized sludge is also taken.

Capital costs include materials, labor, equipment, electrical, normal excavation, and contractor overhead and profit. Labor requirements include one full-time operator for the hours the system is in operation. One-quarter time of system operation is assumed for maintenance.

Table X

Liquid sludge disinfection component costs*

a. Thermal pasteurization costs ($/thousand gallons of sludge flow)

Cost Component	Sludge Flow (thousands of gallons/day)				
	20	100	300	500	750
Capital (0% interest)	1.75	.47	.27	.23	.21
Labor	2.26	1.22	.86	.62	.44
Electric power	.10	.04	.02	.01	.01
Maintenance materials	.98	.23	.11	.08	.07
Fuel ($2/M Btu)	2.15	2.15	2.15	2.15	2.15

b. Irradiation costs ($/thousand gallons of sludge flow)

Cost Component	Sludge Flow (thousands of gallons/day)				
	20	100	300	500	750
Capital (0% interest)	3.04	1.48	1.13	1.05	1.00
Labor	3.26	.65	.24	.16	.11
Electric power	.64	.17	.08	.06	.05
Maintenance materials	.42	.26	.21	.20	.19
^{137}Cs γ-source (0% interest)	2.10	2.00	2.00	2.00	2.00
(7% interest)	6.10	5.90	5.90	5.90	5.90

c. Thermoradiation costs ($/thousand gallons of sludge flow)

Cost Component	Sludge Flow (thousands of gallons/day)				
	20	100	300	500	750
Capital (0% interest)	2.67	.96	.57	.48	.45
Labor	4.56	1.91	.34	.22	.16
Electric power	.83	.25	.12	.12	.10
Maintenance materials	.36	.19	.13	.12	.11
Fuel ($2/M Btu)	2.02	2.02	1.68	1.68	1.68
^{137}Cs γ-source (0% interest)	.80	.60	.60	.60	.60
(7% interest)	2.00	1.80	1.80	1.80	1.80

*Costs were prepared by Scott Ahlstrom, Battelle, PNL, based on Sandia's irradiator design.

Table XI

Dry sludge irradiation component costs*
($/dry ton of sludge)

Component Costs	Material Irradiated (dry tons/day) 5	12.5	25	50
Capital (0% interest)	13.53	8.93	5.52	4.10
Labor	3.10	2.68	2.54	2.47
Electric power	.22	.14	.10	.05
Maintenance materials	.10	.05	.03	.03
^{137}Cs γ-source (0% interest)	3.10	2.60	2.44	2.44
(7% interest)	7.88	7.28	7.14	7.14

*Costs were prepared by Scott Ahlstrom, Battelle, PNL, based on Sandia's irradiator design.

Power requirements are based on positive displacement pump sizes. Fuel requirements were calculated from boiler design data. Maintenance material and supply costs are based on the cost of materials for pumping and on 5 percent of the reactor costs.

2. Radiation Processing

Wet radiation processing costs are based on an engineering design of a pilot plant for Albuquerque, New Mexico. Capital costs include the building and pool, irradiator capsules, deionizer, data acquisition and control system, oxygen injection facility, pumps, piping, equalization tank, and radiation alarm.

Labor requirements include maintenance, operating and monitoring of the system. An allowance is taken to include lab work and a monthly examination of the water by a health physicist.

Power requirements are based mainly on the energy used in equalization, pumping and monitoring the irradiation process. Maintenance material and supply costs take into account normal repair items, rental of a crane once every five years and the purchase of oxygen.

The ^{137}Cs γ-source cost is computed in a fairly complex manner. The useful life of source is assumed to be 60 years, so that with a half-life of 30 years, 25 percent of the source is eventually recycled into the source preparation and disposal system. The cost of the recycled portion of the source is borne by the three source users (20-year plant life) in proportion to the amount of source material that each user depletes. The initial charge is amortized as capital equipment and the recharges every 5 years are regarded as expense. Transportation, loading, and unloading costs are included, and at the end of the plant life, a salvage rate of \$.10/C_i is assumed unless the γ-source is over 60 years old. The Federal Register price of \$.10/Ci f.o.b. Richland, Washington, is also assumed.

3. Thermoradiation

Thermoradiation costs are based on the same parameters as wet irradiation except an allowance is taken in all cases for a boiler and steam injection system. The water temperature is maintained at 55 C. Because of the heat, a smaller radiation dose is applied, thus reducing the capital outlay for irradiator capsules and housing facilities.

4. Liquid Process Cost Summary and Conclusions

The curves in Figure 10 illustrate that the costs are very similar for thermal pasteurization, irradiation, and thermoradiation with a 20-year amortization schedule at 0 percent interest. Lime stabilization is the least expensive process, but the biological effects are unknown. Ascaris eggs would probably not be affected by liming. Irradiation is the most expensive process, followed closely by thermoradiation and pasteurization. Fuel price hikes up to $4.00/MBtu are possible (probable) by 1985; and pasteurization would become the most expensive process.

Most of the increase in total cost for irradiation in the 7 percent irradiation curve in Figure 11 is the interest charge on the initial γ-source loading. No similar interest is charged on the fuel oil.

Dry Sludge Processing Costs--The dry disinfection cost comparisons were made for composting and dry irradiation of compost-like material.

1. Dry Irradiation

Dry irradiation costs in Table XI are based on experience from a pilot plant currently under construction at Sandia Laboratories. The capital costs include site preparation, concrete work, grouting, stainless steel tank materials, steel reflector plates, access ladders, pumps, ventilator, filters, hoists, lead shield door, source plaque and drives, fire suppression system, radiation alarm system, conveyor assembly, a hopper for loading the conveyor and miscellaneous mechanical work plus installation.

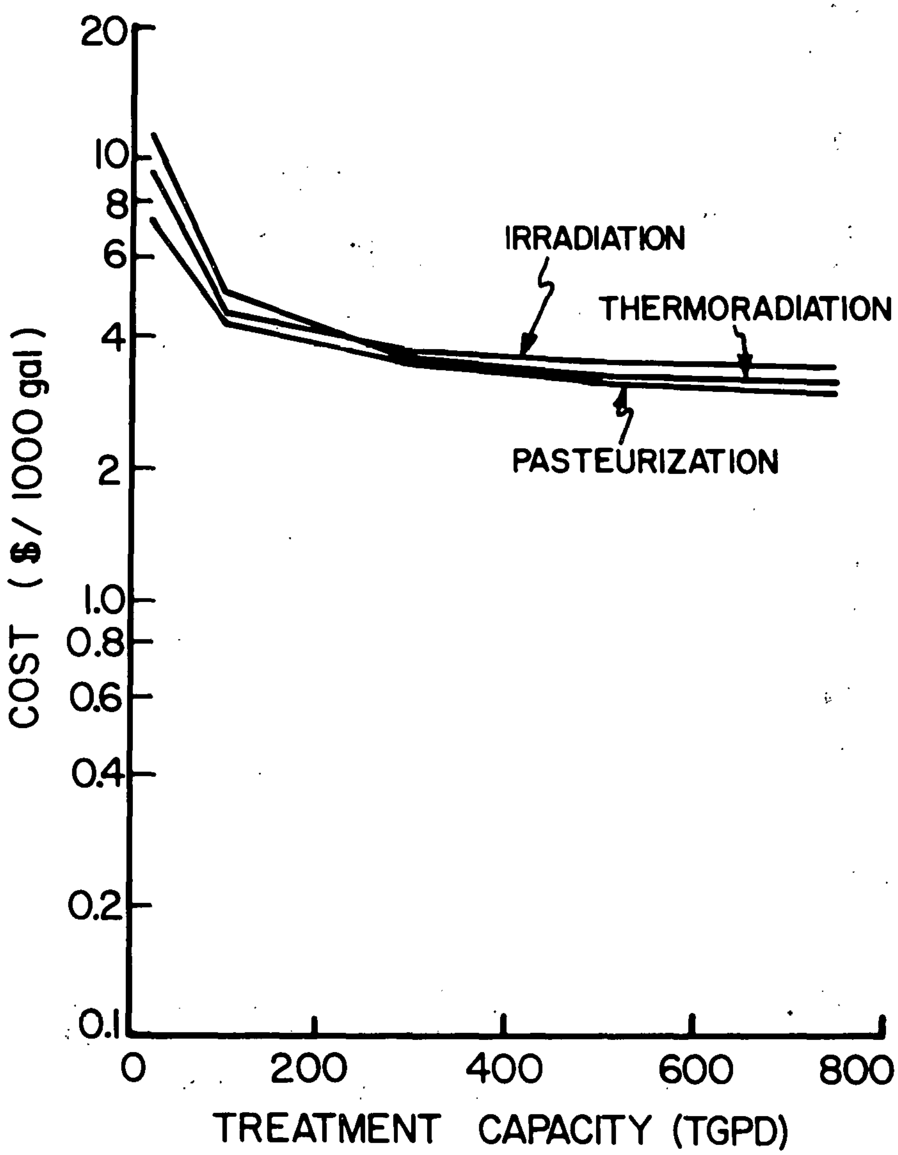

Figure 10. Liquid sludge processing costs.
(No interest; fuel @ $2/M Btu)

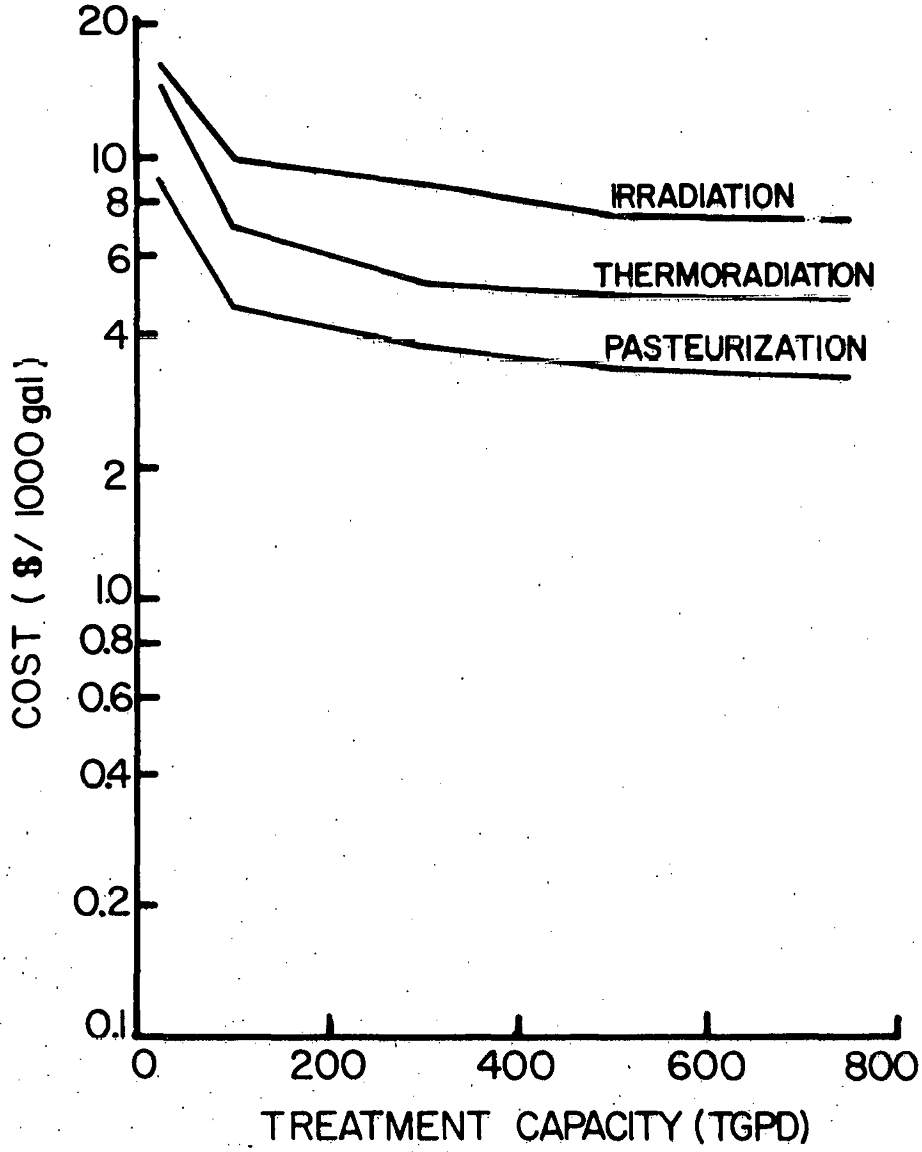

Figure 11. Liquid sludge processing costs.
(7% interest; fuel @ $2/M Btu)

Labor requirements include loading the feed hopper, maintenance of the conveyor assembly, and a periodic check of the filters.

Power requirements include the belt drive, air blower, and radiation alarms.

Material and supplies costs arise from replacement of the filters and maintenance of the conveyor assembly.

2. Composting

Available cost data on the static pile composting method was extremely variable and no reliable, nationally applicable cost curve was developed. The information gathered and plotted came from work done by the Agricultural Research Service at Beltsville, Maryland, and a survey of static pile composting costs done by Culp/Wesner/Culp. Costs include site development, equipment, and operating costs. They do not include land costs, treatment of runoff, final disposal, transportation or dewatering. Site development costs were amortized over 30 years, equipment costs over 10 years, and land over an infinite period of time, all at 7 percent interest.

3. Dry Process Cost Summary and Conclusions

As indicated in Figure 12, composting is substantially more expensive than irradiation at any reasonable interest rate. The two processes are not equivalent, however, in that composting is also a drying operation to get the sludge from 16 percent solids up to about 50 percent solids, while stabilizing the sludge. Static composting is a fairly dirty operation and recontamination of already composted sludge is commonplace. Irradiation could provide a final processing to the bagged compost to eliminate virtually any pathogen-related public health concerns.

Dry heating processes could be devised for disinfecting the compost, but none are known to be in use. Energy costs for such processes using very reasonable assumptions would be

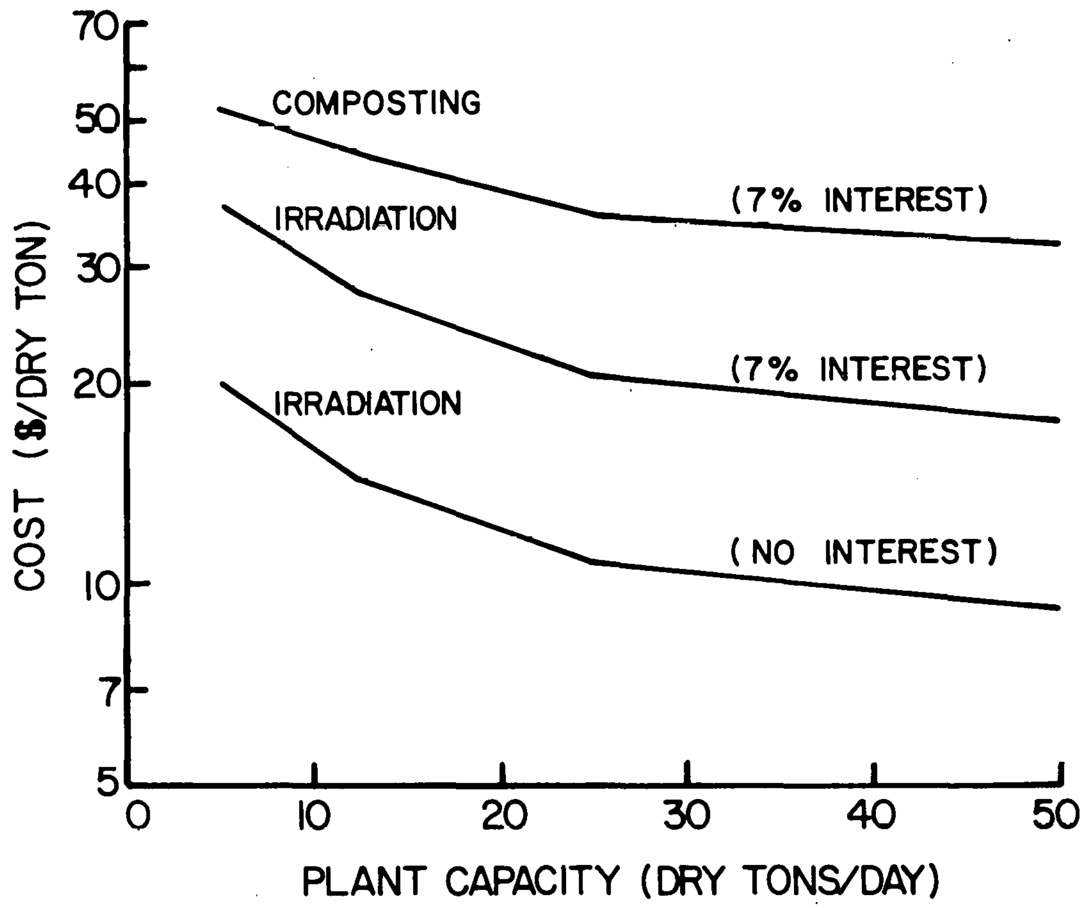

Figure 12. Dry sludge processing costs.

very similar to γ-source costs for irradiation. The capital costs would probably be lower.

Animal Refeeding and Agronomics Programs *

A cooperative research program involving the New Mexico Agricultural Experiment Station at New Mexico State University, Las Cruces (NMSU) and Sandia Laboratories, Albuquerque (SANDIA) was initiated in 1975 under contract with the U. S. Energy Research and Development Administration (Albuquerque Operations Office) and is projected to continue through 1981. SANDIA has developed technology for destruction of pathogens by thermoradiation and has provided NMSU with thermoradiated (combined heat and gamma irradiation) and irradiated sewage solids for assessment of nutritive value.

Animal Refeeding Program--Although the NMSU program, to date, has not been primarily "toxicological" in design, considerable attention has been given to measurement of potential toxicants in the sewage products fed and to assessment of apparent toxicity in experimental animals.

Sewage products were analyzed chemically and then studied in cultures of rumen microorganisms to assess effects on microbial degradation of fibrous substrates. In these studies, sewage products were compared with cottonseed meal and urea, when provided in isonitrogenous amounts. When assayed in terms of fiber degradation, the solids from undigested ("raw") sewage supported greater fermentative activity ($P < .05$) than either cottonseed meal or urea, suggesting nutritive benefits in addition to the nitrogen provided (Smith *et al.*).[18] In these studies, microscopic examinations of the microbial populations showed normal numbers of typical rumen protozoa, suggesting that the sewage solids were relatively non-toxic to these sensitive organisms. Likewise, rather large amounts of sewage solids (80 to 220 grams daily) have been placed directly into the forestomachs (via rumen cannulae) of rumen-fistulated sheep fed conventional and experimental diets for extended periods (20 to 50 days) without apparent adverse effects on feed intake, animal appearance and behavior, or presence of typical protozoa in the rumen fluid.

*"a portion of the material presented in this paper also was included in the papers, "Recycling Sewage Solids as Feedstuffs" and "Recycling Sewage Solids as Fertilizer," published in *Food, Fertilizer, and Agricultural Residues*, Ann Arbor Science Publishers Inc., 1977."

Prior to, or concurrent with, feeding experiments with sheep and cattle, the sewage products evaluated have been tested in long-term feeding experiments with rats, whereby male and female rats were fed diets comprised of commercial chow with up to 50 percent by weight of added sewage product from weaning through young adulthood and one or two phases of reproduction. Although the products used provided little nutritive value to rats (as expected), the growth, appearance and reproductive performance of rats fed thermoradiated sewage solids suggested little, if any, adverse effect other than dilution of dietary nutrients. Balance trials with such diets indicated that most of the dietary heavy metals and (selected) trace elements with potential for toxicity were excreted in the feces; however, some enlargement of livers was noted, and tissue retention (livers and kidneys) of certain elements (notably Fe and Cu) suggested possible adverse effects from long-term feeding of products tested. Data from typical experiments with rats have been reported (Smith *et al.*)[18]

Nutritive Evaluation with Sheep

In a series of short-term digestibility trials with sheep fed basal, fibrous, "poor-quality" (low-nitrogen) diets in comparison with equal intakes of basal components plus supplemental cottonseed meal (CSM) *versus* irradiated, undigested sewage solids, digestibility of basal components was apparently improved by supplements, and sewage solids compared favorably with CSM. Apparent digestibility of energy in the supplements (calculated by difference in total energy digested for basal *versus* supplemented diets) varied from 40 to 60 percent for sewage solids in comparison with 58 to 65 percent for CSM. Likewise, apparent digestibility of supplement nitrogen (calculated by difference) ranged from 50 to 60 percent for sewage solids as compared with 67 to 73 percent for CSM. In the most definitive of these trials, the calculated true digestibility of supplement nitrogen (calculated by difference and corrected for metabolic fecal nitrogen based on literature values), was 82.8 ± 5.7 percent for sewage solids *versus* 82.2 ± 1.7 percent for CSM ($\bar{x}$ ± S.D., three lambs each diet). These data were reported earlier (Smith *et al.*).[18]

More recent experiments evaluated sewage solids collected from the Albuquerque sanitation district, and processed by centrifugation (to enrich solids from about 5 percent to about 20 to 25 percent) prior to irradiation and drying by forced-air ventilation in vats lined and covered with plastic. This product (TRUSC) was sampled, analyzed chemically, processed through a hammer mill, and incorporated into experimental diets at levels comprising 10, 20 or 30 percent of diet dry matter. Comparable diets were formulated to contain 5, 10 or 15 percent cottonseed meal (CSM), and a control ("BASAL") diet was formulated to be somewhat similar but without either CSM or TRUSC. All diets were pelleted at a local feed mill. The ingredient composition and crude protein content of these diets are shown in Table XII. Chemical composition of the TRUSC is shown in Table XIII.

Commercial crossbred lambs were group-fed these diets (with salt and water _ad libitum_) for 29 days during which time feed intake and body weight changes were recorded. Thereafter, all lambs were provided a commercial, pelleted, finishing diet for feeder lambs, and feeding performance was evaluated during 100 days. The results, reported elsewhere (Cadle _et al_.),[19] showed poor intake of diets with TRUSC during the first two weeks, but acceptable intakes thereafter. Some of these lambs were maintained on 30 percent TRUSC for 69 days and achieved intakes approaching 4 percent of body weight. Feeding of TRUSC did not adversely affect subsequent feeding performance.

Concurrent with the feeding trial, selected lambs in each of three diet groups (Basal _versus_ 10 percent CSM _versus_ 20 percent TRUSC) were fitted with fecal collection bags and used in a 10-day digestion trial while consuming the diets _ad libitum_ under group-feeding conditions. Total fecal collections were accomplished and dietary intakes calculated from fecal lignin output and dietary lignin content. Energy and nitrogen intakes and digestibility were calculated. These data are summarized in Table XIV. Digestibility of both energy and nitrogen was improved by CSM or TRUSC over the basal diet, and the amounts of digested energy and digested nitrogen were greater for lambs fed 20 percent TRUSC than for those fed 10 percent CSM. (The

Table XII

Ingredients and protein content of diets fed to sheep and cattle[1/]

Ingredients, %	Diets						
	BASAL	5% CSM	10% CSM	15% CSM	10% TRUSC	15% TRUSC	30% TRUSC
Sorghum stover	40.0	45.0	40.0	35.0	45.0	40.0	35.0
Alfalfa hay	30.0	27.0	24.0	21.0	27.0	24.0	21.0
Sorghum grain	24.7	18.2	21.6	24.8	13.3	11.5	9.8
Cane molasses	5.0	4.5	4.0	3.5	4.5	4.0	3.5
Cottonseed meal (CSM)	none	5.0	10.0	15.0	none	none	none
TRUSC[2/]	none	none	none	none	10.0	20.0	30.0
Phosphorus supplement[3/]	0.3	0.3	0.4	0.7	0.2	0.5	0.7
Protein content, %	11.0	11.2	12.8	14.0	10.9	11.8	12.0

[1/] NMSU experiments, summer 1976.

[2/] TRUSC represents undigested sewage solids from Albuquerque, NM, irradiated at Sandia Laboratories, Albuquerque, NM.

[3/] "X-P-4"®, commercial poly-phosphate supplement.

Table XIII

Chemical composition of irradiated, undigested sewage solids fed to sheep[1/]

Components	Content (% of dry matter)
Ash (550°C)	29.6
Crude silica	14
Ether extract	13.1
Nitrogen (Kjeldahl; HgO catalyst)	2.89
Crude protein (N x 6.25)	18.1
Acid-detergent fiber	33 [2/]
Acid-detergent lignin	8 [2/]
Heat of combustion	4.65 Kcal/g
Calcium, as Ca	1.85
Phosphorus, as P	0.71
Magnesium, as Mg	.251
Sodium, as Na	.143
Potassium, as K	.209
Trace Elements[3/]	(ppm)
Ag	25
Cd	12
Co	5
Cr	192
Cu	636
Fe	5040
Hg	4
Mn	107
Pb	99
Zn	1147

[1/] Used in NMSU experiments with sheep and cattle, summer, 1976.

[2/] Data expressed on ash-free basis.

[3/] Values represent total content, as measured by atomic absorption spectrophotometry using acidic solutions from wet-ashed samples.

Table XIV

Digestibility of energy and nitrogen in fibrous diets for lambs as affected by cottonseed meal (CSM) or irradiated, undigested sewage solids (TRUSC)[1], [2]

Items	Diets		
	BASAL	10% CSM	20% TRUSC
Lambs per group	4	4	4
Energy intake, Kcal/(Kg BW)$^{.75}$	375±76[3]	378±43	400±63
Energy digested, Kcal/(Kg BW)$^{.75}$	191±57	191±17	214±27
Energy digestibility, %	50±6	51±2	54±3
Nitrogen intake, g/(Kg BW)$^{.75}$	1.69±.34	2.04±.23	1.96±.31
Nitrogen digested, g/(Kg BW)$^{.75}$	.68±.24	.91±.09	.93±.18
Nitrogen digestibility, %	39±7	45±1	47±3

[1] NMSU experiments, summer 1976.

[2] TRUSC represents undigested sewage solids from Albuquerque, NM, irradiated at Sandia Laboratories, Albuquerque, NM.

[3] Values shown are means ± standard deviations.

data in Table XIV are presented in terms of nutrients consumed and nutrients digested per unit of metabolic body size (Kg Body Weight)$^{.75}$, in order to facilitate comparisons with similar data for cattle, presented in Table XV and described below).

The same diets studied with sheep were also fed to steers penned separately and offered diets in amounts calculated at 2 to 3 percent of body weight. Diets were fed during a 10-day adjustment period and a 5-day collection period during which time total feces were collected by fitting the animals with fecal collection bags. Dietary intakes and fecal outputs were measured directly and digested nutrients calculated by difference. The data (shown in Table XV) show that CSM and TRUSC tended to increase the amounts of digested energy and nitrogen beyond the levels for the basal diet and tended to improve digestibility of dietary energy and nitrogen over the basal diet. TRUSC at 20 percent of the diets provided slightly more digested energy and digested nitrogen than CSM at 10 percent of the diet. Although the differences between diets are not statistically significant ($P > .05$) because the numbers of individuals are small and individual variations are relatively large, the trends suggest nutritive value of sewage products which has biological and economic importance.

Tissue Retention of Heavy Metals and Trace Elements

Attention has been given to potential hazards of heavy metals and organic pollutants in the food chain arising from land application of sewage sludges (Dean;[20] CAST[21]). Sheffner *et al.*[22] discussed toxicological aspects in the nutritional evaluation of activated sludge and presented data on growth, reproductive performance and teratology of rats and rabbits, and egg production by chickens fed sewage products. Adverse effects were noted in terms of production when sewage products were used at 10 percent or more of diets, but levels of 5 percent or 10 percent of the diet did not result in gestational or teratogenic abnormality. Cheeke and Myer[23] evaluated activated sewage sludge as a protein source for rats and Japanese quail, but reported no data on tissue composition. Schönborn[24] cited reports, mostly from European literature, concerning

Table XV

Digestibility of energy and nitrogen in fibrous diets for cattle as affected by cottonseed meal (CSM) or irradiated undigested sewage solids (TRUSC)[1], [2]

Items	Diets		
	BASAL	10% CSM	20% TRUSC
Steers per group	4	4	4
Energy intake, Kcal/(Kg BW)$^{.75}$	280±9[3]	284±9	316±24
Energy digested, Kcal/(Kg BW)$^{.75}$	127±30	152±26	171±25
Energy digestibility, %	45±10	53±7	54±9
Nitrogen intake, g/(Kg BW)$^{.75}$	1.31±.05	1.53±.05	1.55±.12
Nitrogen digested, g/(Kg BW)$^{.75}$	.46±.20	.76±.15	.80±.09
Nitrogen digestibility, %	35±15	59±8	50±8

1/ NMSU experiments, summer 1976.

2/ TRUSC represents undigested sewage solids from Albuquerque, NM, irradiated at Sandia Laboratories, Albuquerque, NM.

3/ Values shown are means ± standard deviations.

nutritive value of sewage products for rats, poultry and swine, and discussed potential hazards of chemical toxicants. Recently, Kinzell, Cheeke and Chen[25] reported growth, organ size, tissue heavy metals and trace elements, reproductive performance and pentobarbital sleeping times of rats as affected by dietary activated sewage sludge. Although growth and reproductive performance were adversely affected, livers and kidneys were enlarged, and pentobarbital sleeping times suggested liver metabolism of some toxic constituents in the product fed, heavy metals (Cd, Hg and Pb) were not accumulated "beyond acceptable levels" in the muscle tissue, even when sludge comprised 50 percent of the diet. Metals contents (Cd, Cu, Fe, Hg, Mn, Pb, and Zn) in livers, kidneys, hearts, spleens, testes, muscles, brains, etc., from rats fed activated sewage sludge at 50 percent of the diet were reported.

Although it is generally recognized that ruminants are the animals with greatest potential for direct refeeding of sewage solids, and that data from non-ruminants are often unapplicable for ruminants, there are very few reports in the American literature on tissue retention of heavy metals, trace elements and organic toxicants by ruminants fed sewage products. Kienholz, Ward, and Jonnson[26] presented preliminary results from studies of heavy metals and organic toxicants in tissues of cattle grazing forages from sludge-treated soils, and of cattle fed digested sludge in feedlot. These Colorado researchers reported further results, indicating measureable tissue levels of certain metals, pesticide residues and chlorinated hydrocarbons, at the Third National Conference on Sludge Management, Disposal and Utilization (Miami, Flordia; December 1976; Proceedings in press; Information Transfer, Inc., Rockville, Maryland).

Data have been reported on apparent absorption and retention of heavy metals and certain trace elements by sheep fed thermoradiated undigested sewage solids (Smith _et al_.).[18] Those data, based on analysis of feeds, feces and urine from short-term balance trials, showed that absorption of Ag, Cd, Co, Cr, Cu, Fe, Hg, Mg, Mn, Pb, and Zn from sewage solids was low. These elements from ingested sewage products were excreted mainly in the feces. However, positive balances were recorded in some cases; although amounts detected in livers from six sheep fed sewage products at levels of 20 to 30 percent of diet dry matter for about three months were not appreciably elevated over comparable values for experimental control animals. Likewise, blood samples from sheep fed sewage solids at 20 to 30 percent of diet showed no appreciable difference in content of heavy metals or trace elements when compared to experimental controls. These same trends have been confirmed and reported in subsequent studies (Bruce, et al.).[28]

In more definitive experiments (reported originally herein) samples of blood were taken from sheep fed the experimental diets shown in Table XIII after 29 days feeding and other samples were obtained from sheep fed two of these diets (15 percent CSM and 30 percent TRUSC) after an additional 40 days. Contents of heavy metals and trace elements in these samples are shown in Tables XVI and XVII. These data show that blood levels of the heavy metals and trace elements measured were not appreciably affected by dietary sewage solids.

Samples of livers and kidneys were collected from sheep fed the basal diet or 30 percent TRUSC for 69 days and then fed a pelleted, commercially-prepared conventional sheep diet for 61 days. Likewise, samples of kidneys were collected from sheep fed the 30 percent TRUSC diet for 29 days and then the conventional diet for 104 days. Elemental composition of these livers and kidneys is shown in Tables XVIII and XIX. The results show that ingestion of TRUSC at 30 percent of the diet for 29 or 69 days, followed by a conventional diet for 104 or 61 days, failed to significantly affect liver and kidney contents of Ca, P, Na, K, Fe, Cu, Mg, Mn, Zn, Co, and Cr. In the cases of Ag, Cd, Hg, and Pb, the means for values from animals fed TRUSC were slightly higher than comparable means for control animals; suggesting slight increases in content of these elements as a result of ingested TRUSC. The values (in ppb) for Hg in livers (<14 for "controls" versus 31 ± 10 for "experimentals") and for Pb in kidneys (148 ± 13 for "controls" versus 281 ± 24 and 226 ± 35 for "experimentals") indicate significant increases ($P < .05$) in these elements as

Table XVI

Elemental composition of whole blood in lambs as affected by diets with and without sewage solids[1/], [2/]

Elements	BASAL	5% CSM[3/]	10% CSM	15% CSM	10% TRUSC[3/]	20% TRUSC	30% TRUSC
	Diets						
	mg/100 ml						
Ca	6.2±2.7	4.3±0.6	4.1±0.6	3.7±1.1	4.3±0.9	4.8±0.8	5.3±0.9
P	17.9±1.5	18.4±1.6	19.4±1.7	22.1±1.8	20.1±1.3	19.2±2.2	18.4±1.0
Na	201±6	203±2	203±2	207±1	204±2	206±5	208±5
K	44±11	31±4	35±2	37±6	31±3	36±13	34±5
Fe	38±4	38±5	38±2	34±5	45±12	38±5	35±7
Mg	2.5±.3	2.4±.3	2.5±.1	2.5±.2	2.3±.2	2.6±.1	2.5±.1
	μg/100 ml						
Ag	------------	------------	------------	<3.6*	------------	------------	------------
Cd	------------	------------	------------	<2*	------------	------------	------------
Co	------------	------------	------------	<1.4*	------------	------------	------------
Cr	------------	------------	------------	<7.8*	------------	------------	------------
Cu	93±9	102±8	94±16	102±6	98±0	115±13	96±4
Hg	65±13	54±18	70±16	45±7	75±13	66±9	62±10
Mn	------------	------------	------------	<4*	------------	------------	------------
Pb	24±2	23±5	22±1	23±0	29±3	27±3	26±2
Zn	572±183	522±143	531±135	480±122	535±155	645±75	562±210

[1/] NMSU experiments, summer 1976; diets had been fed for 29 days; samples were wet-ashed and analyzed by atomic absorption spectrophotometry.

[2/] Values shown are means ± standard deviations representing 4 lambs for each group.

[3/] CSM is cottonseed meal; TRUSC is irradiated undigested sewage solids from Albuquerque, NM.

* Values represent limits of detection under analytical conditions used.

Table XVII

Elemental composition of whole blood in lambs as affected by diets with cottonseed meal (CSM) or irradiated sewage solids (TRUSC)1/, 2/

Elements		Diets	
		15% CSM	30% TRUSC
		mg/100 ml	
Ca		5.7±.6	5.6±1.3
Na		260±30	265±10
K		37±10	39±6
Fe		45±9	45±7
Mg		1.2±.3	1.2±.4
		μg/100 ml	
Ag	all <3.6*		
Cd		6.0±1.4	6.2±.7
Co	all <1.4*		
Cr	all <7.8*		
Cu		164±7	162±8
Hg		48±20	37±10
Mn	all <4*		
Pb		49±4	34±1
Zn		259±17	245±40

1/ NMSU experiments, summer, 1976; diets had been fed for 69 days; samples were wet-ashed and analyzed by atomic absorption spectrophotometry.

2/ Values shown are means ± standard deviations representing 6 lambs per group.

*Values represent limits of detection under analytical conditions used.

Table XVIII

Elemental composition of livers from lambs fed diets with and without irradiated undigested sewage solids (TRUSC)[1/], [2/]

Dietary Regimen	Livers	
	BASAL, 69 days	30% TRUSC, 69 days
	Conventional diet, 61 days	
Number of lambs	5	5
Elements	mg/Kg (ppm), fresh tissue	
Ca	52 ± 14	58 ± 4
P	3824 ± 236	3646 ± 128
Na	783 ± 42	748 ± 57
K	2819 ± 174	2679 ± 138
Fe	63 ± 10	87 ± 13
Cu	95 ± 18	93 ± 22
Mg	183 ± 9	177 ± 1
Mn	3.1 ± .4	3.0 ± .3
Zn	35 ± 2	35 ± 2
	µg/Kg (ppb), fresh tissue	
Ag	950 ± 119	1182 ± 146
Cd	78 ± 34	90 ± 13
Co	<50*	<50*
Cr	<60*	<60*
Hg	<14*[a/]	31 ± 10[b/]
Pb	226 ± 44	285 ± 66

1/ NMSU experiments, summer, 1976; samples were wet-ashed and analyzed by atomic absorption spectrophotometry.

2/ Values shown are means ± standard deviations.

* Values represent limits of detection under analytical conditions used.

a/, b/ Values with different superscript letters are significantly different ($P < .05$).

Table XIX

Elemental composition of kidneys from lambs fed diets with and without irradiated undigested sewage solids (TRUSC)[1/], [2/]

Dietary Regimen	Kidneys		
	BASAL, 69 days	30% TRUSC, 69 days	30% TRUSC, 29 days
	Conventional diet, 61 days		Conventional diet, 104 days
Number of lambs	4	5	6
Elements	mg/Kg (ppm), fresh tissue		
Ca	75 ± 14	86 ± 11	79 ± 15
P	6163 ± 267	5799 ± 356	6089 ± 516
Na	1903 ± 228	1664 ± 151	1703 ± 102
K	2641 ± 141	2481 ± 208	2565 ± 283
Fe	59 ± 16	52 ± 11	54 ± 18
Cu	3.3 ± .2	3.3 ± .3	3.4 ± .3
Mg	182 ± 10	172 ± 7	181 ± 17
Mn	1.2 ± .1	1.2 ± .2	1.2 ± .1
Zn	19 ± 1	24 ± 2	23 ± 3
	μg/Kg (ppb), fresh tissue		
Ag	<25*	<25*	<25*
Cd	131 ± 104	125 ± 13	81 ± 8
Co	<50*	<50*	<50*
Cr	<60*	<60*	<60*
Hg	<14*	<14*	<14*
Pb	148 ± 13[a/]	281 ± 24[b/]	226 ± 35[b/]

1/ NMSU experiments, summer, 1976; samples were wet-ashed and analyzed by atomic absorption spectrophotometry.

2/ Values shown are means ± standard deviations.

* Values represent limits of detection under analytical conditions used.

a/, b/ Values with different superscript letters are significantly different ($\overline{P}$ < .05).

a result of earlier ingestion of sewage solids; although the biological importance of these differences is questionable.

Heavy metals and potentially toxic trace elements tend to accumulate in livers and kidneys at levels higher than in muscle tissue and other typically edible meat products, and therefore, levels of these elements in livers and kidneys can be regarded as indicators of potential hazards to the human food chain. On this basis, the results presented herein suggest that feeding of TRUSC, followed by prolonged feeding of a conventional diet, poses little if any hazard from the elements assayed to consumers of meat products. It should be noted, however, that livers and kidneys are not necessarily the most important tissues to assay for possible hazards to the animals consuming contaminated feedstuffs, since chronic toxicity may relate more closely to levels accumulated in other tissues such as brain, bone, lung, spleen, etc. These tissues have not been analyzed to date in our studies.

The data in Tables XVIII and XIX provide two notable observations, one of which has been widely recognized: copper accumulates in livers of sheep at levels much higher than in kidneys; whereas cadmium accumulates at higher levels in kidneys. Less frequently discussed in literature we have seen is the observation that silver (Ag) accumulated in livers at 800 - 1300 ppb, but was undetected in kidneys of the same animals. The biological importance of this finding is not known at present.

In our experiments potential organic toxicants such as pesticides, chlorinated hydrocarbons, polychlorinated biphenyls, aflatoxins, etc., have not been measured in the sewage products fed or in animal tissues. Such investigation is obviously of importance and will be conducted with samples from experiments reported herein; although results from our bioassays with rats indicated no apparent adverse effects on reproductive performance from ingestion of sewage products at levels up to 50 percent of diets from weaning through adulthood and one breeding cycle. A very recent report (Rose and Harshbarger)[27] of neoplastic skin lesions in neotenic tiger salamanders from a sewage lagoon suggests chemical etiology and provides further incentive for continued, rigorous research in assessing the hazards of recycled sewage products.

Agronomics Program--The agronomic research program at New Mexico State University encompasses both greenhouse and field plot trials of both undigested and digested sludges. The work reported here deals with undigested and digested liquid sludges which were thermoradiated (150 krad of gamma irradiation at 65 C) for pathogen reduction and air dried. Various properties of the sludges were studied to determine the relative agronomic values of the digested and undigested sludges as well as to assess the effects of the thermoradiation treatment. A greenhouse experiment was used to evaluate the use of the sludges as a source for plant nutrients and of heavy metals. Sludges were added to clay loam soil at rates of 500 and 1,000 pounds total nitrogen per acre. A control and two chemical fertilizer treatments (100 pounds N plus 40 pounds P and 200 pounds N plus 80 pounds P) were included for comparison. Eight week greenhouse trials were run with sorghum grown in plastic pots.

The sludge content of selected heavy metals is shown in Table XX. The higher concentrations in digested sludges are due to the reduction in solids during anaerobic digestion. Digestion sludges also contained higher concentrations of inorganic nitrogen but lower concentrations of total nitrogen.

Dry matter production is shown in Table XXI. The increased production due to sludge application is noteworthy. The increased application rate of digested sludge was necessary in order to apply equivalent amounts of nitrogen in both sludge trials.

The macronutrient content of sorghum tissue at the end of the experiment is shown in Table XXII. The decreased calcium in the undigested treatments is due to the larger amount of dry matter generated. Tissue content of Fe, Zn, Mn, Cu, and Cd are shown in Table XXIII, and again sludge-amended trials must be considered in terms of the increased dry matter production. It is also interesting to note the Cd level of the control (no amendments) versus the level in sludge-amended soil. Plant tissue concentrations in both Tables XXII and XXIII did not exceed suggested tolerance levels

Table XX

Total, HCl, DTPA and H_2O extractable Fe, Cu, Zn, Mn, Cr, Cd, Pb in undigested (USS), thermoradiated undigested (TRUSS), digested (DSS) and thermoradiated digested (TRDSS) sewage sludge.

Extractant	Fe	Zn	Cu	Mn	Cr	Cd	Pb
	ppm						
	Undigested						
Total	10771	1364	852	145	194	15	626
HCl	4155	975	372	89	35	10	397
DTPA	795	352	45	19	.5	4	183
H_2O	9	16	3	4	*	**	.1
	Thermoradiated Undigested						
Total	10864	1333	796	143	194	14	608
HCl	4248	971	374	88	38	10	403
DTPA	809	310	40	19	.5	3	184
H_2O	8	16	3	4	*	**	.1
	Digested						
Total	14671	1684	1132	236	379	26	678
HCl	3389	1580	577	150	74	25	525
DTPA	156	437	145	14	.6	8	72
H_2O	2	11	6	2	*	**	.02
	Thermoradiated Digested						
Total	14857	1676	1121	234	394	27	676
HCl	3204	1528	560	144	68	24	512
DTPA	166	421	161	14	.6	8	74
H_2O	2	11	6	2	*	**	.03

*<.5 ppm Cr

**<.125 ppm Cd

Table XXI

Average dry matter production at termination of greenhouse experiment as a result of fertilizer and sludge treatments

Treatment	Yield (g/pot)
Control (No fertilizer or sludge)	.159
100-40-0	.142
200-80-0	.242
USS (9 ton/A)*	1.770
USS (18 ton/A)	2.973
TRUSS (9 ton/A)	1.782
TRUSS (18 ton/A)	2.443
DSS (15 ton/A)**	.554
DSS (30 ton/A)	1.480
TRDSS (15 ton/A)	.426
TRDSS (30 ton/A)	1.538

*Available nutrients equivalent ~200-60-0

**Available nitrogen equivalent to 9 ton/A USS

Table XXII

Macronutrient content of sorghum tissue at termination of greenhouse experiment

Treatment	N	P	K	Ca	Mg
	percent of dry matter				
Control	3.00	.59	3.48	1.37	.50
100-40-0	2.83	.57	3.28	1.38	.47
200-80-0	2.48	.49	3.37	1.59	.48
USS (9 ton/A)	2.63	.60	3.58	.77	.47
USS (18 ton/A)	2.40	.56	3.67	.89	.48
TRUSS (9 ton/A)	2.33	.59	3.55	.88	.49
TRUSS (18 ton/A)	2.35	.58	3.49	.86	.47
DSS (15 ton/A)	2.38	.59	3.74	1.07	.47
DSS (30 ton/A)	1.81	.56	3.33	1.02	.49
TRDSS (15 ton/A)	2.22	.44	3.52	1.11	.45
TRDSS (30 ton/A)	2.00	.51	3.08	1.10	.47

Table XXIII

Sorghum tissue concentration of Cu, Mn, Fe, Zn and Cd at termination of greenhouse experiment

Treatment	Fe	Zn	Mn	Cu	Cd
			ppm		
Control	262	62	63	31	4.0
100-40-0	204	68	69	37	3.3
200-80-0	176	55	62	20	3.9
USS (9 ton/A)	95	133	55	29	3.6
USS (18 ton/A)	90	177	47	35	3.7
TRUSS (9 ton/A)	96	131	63	26	3.3
TRUSS (18 ton/A)	93	170	54	29	4.0
DSS (15 ton/A)	192	128	72	24	4.8
DSS (30 ton/A)	105	138	63	27	4.6
TRDSS (15 ton/A)	147	118	67	33	4.3
TRDSS (30 ton/A)	98	129	58	35	4.2

for any of the elements examined. Plant uptake of both nutrients and heavy metals was greater for sludge treatments than for the control due largely to increases in plant growth. The thermoradiation treatment did not significantly affect dry matter production or plant uptake of any elements. It did affect plant concentrations of Ca, Fe, Zr, and P, but the effect was slight and of no practical importance. It should be noted that digestion concentrates metals, decreases available nitrogen and is a process which subtracts value from this potentially valuable resource.

Studies are also under way looking at soils which have been receiving sludges for 42 years (Clovis, NM) and soils which have been receiving raw sewage (Juarez, Mexico). These will be evaluated for physical and chemical effects as well as pathogen source potential.

Product Enhancement

Ammonia production in the U. S. is based wholly on natural gas. Approximately 2 percent of the annual domestic consumption of natural gas is used in the industrial synthesis of anhydrous ammonia which, in turn, is used either as is or as a feedstock for the production of various ammonium salts. These are primarily used as nitrogen fertilizers for modern agriculture. The recent increases in natural gas rates have correspondingly driven up nitrogen fertilizer prices which has been a cause for some concern in the agricultural community.

In light of these developments, the recovery of this evermore costly commodity from wastewater has become an attractive research option. The major nitrogen form in wastewater is initially urea, but this is rapidly degraded in raw sewage to ammonia and CO_2 by urease-producing microorganisms.

During aerobic water treatment processes, however, a large fraction of the ammonia is oxidized to nitrate. Because neither nitrate nor ammonia are desirable constituents of a final effluent, tertiary treatment schemes may include a denitrification step or an ammonia-stripping process.

In typical denitrification, effluent from activated sludge or from a deliberate nitrification pretreatment (equivalent to a high-rate oxygen activated sludge process) is treated batch-wise in anaerobic columns. These columns contain certain bacteria that, under anaerobic conditions, reduce nitrate, via nitrite, to N_2 or N_2O. These gases are then released to the atmosphere. This biological process is known as dissimilatory denitrification.

Many microorganisms are also capable of a second type of nitrate reduction known as assimilatory denitrification. Nitrate is again reduced to nitrite, but the nitrite is reduced to ammonia rather than N_2. This pathway is, however, subject to ammonia repression. That is, the presence of exogenous ammonia causes assimilatory denitrification to cease. This is economical on the part of the cell because it has no need to produce ammonia from nitrate when a sufficient supply is already available. Mutant strains in which this control mechanism is in some way defective, however, continue to reduce nitrate in the presence of ammonia. Such derepressed mutants have been produced in the filamentous fungus, Aspergillus nidulans.[29]

The use of a similar bacterial mutant in place of dissimilatory denitrifiers for wastewater treatment would reduce influent nitrate to ammonia, which could then be removed by ammonia-stripping. Clinoptilolite, a zeolite clay with a high affinity for ammonia, is now used as an ion-exchange medium in ammonia-stripping. The ammonia can, in turn, be steam-stripped from clinoptilolite, the vapor passed through an appropriate acid, e.g., sulfuric acid, and ammonium salts recovered, e.g., ammonium sulfate.

An alternative non-biological approach is also being considered. Namely, ammonia removal by the process just described, prior to aerobic wastewater treatment when the majority of the wastewater nitrogen is still in ammonia form. Possible problems, such as clogging of the clinoptilolite beds by suspended particulates, etc., must be investigated before feasibility can be demonstrated.

In either case, the ammonia (as ammonium sulfate) that could on the average be recovered from domestic wastewater would, if added to the accompanying sludge (waste activated sludge was included in the calculation) result in a product containing ~8 percent available nitrogen. Domestic sludge has usually only 2 - 3 percent available nitrogen. This would increase the bulk value of the product sludge from a current $25/ton to an estimated $95/ton.

The ultimate success of a biological approach hinges on the production of mutant strains with the appropriate characteristics that are also hardy enough to perform well under actual plant operating conditions.

Work to develop such a strain has begun. Selection of a promising candidate organism was based on several criteria. It must be non-pathogenic, grow over a reasonably broad range of environmental conditions, utilize a variety of carbon sources, be facultatively anaerobic, and, of course, reduce nitrate efficiently.

Chromobacterium violaceum was selected on the basis of these criteria. It is a Gram-negative non-pathogenic motile rod that reduces nitrate and nitrite anaerobically. Assimilatory nitrate reduction also occurs aerobically but at reduced rates.[30] Aside from an early monograph, the kinetics of anaerobic growth in *C. violaceum* had not been studied in detail.[31] Growth studies, with particular attention to nitrogen nutrition, were, initiated.

Anaerobic growth at 37 C in nutrient broth supplemented with glucose was taken as the standard for optimal growth with which other data were compared. Development of a chemically-defined medium that permits good growth was necessary in order to obtain clear-cut results on the influence of varied nitrogen sources and to do mutant selection.

Previous work with aerobically grown *C. violaceum* showed that growth in a minimal salts medium was not enhanced by vitamins. We have demonstrated a similar lack of effect of individual vitamins on anaerobic growth. A marked effect, however, is reportedly produced by certain amino acids.[32] Arginine and methionine, particularly when arginine is also present, stimulates aerobic growth. We have found that arginine (optimal concentration = .25 mg/ml) similarly stimulates anaerobic growth in a minimal salts medium. Methionine, however, has no effect; but, cystine at .005 mg/ml particularly when arginine is also present, has a definite effect. Methionine and cystine both contain sulfur. These similar but distinct findings probably relate to differences in sulfur metabolism during aerobiosis and anaerobiosis but have not been further investigated.

Anaerobic growth in ammonium-free arginine-cystine medium (AC medium) is nearly equivalent to that in nutrient broth (Figure 13). More surprising, however, is the fact that growth in identical basal medium containing ammonium sulfate (2 g/l) as sole nitrogen source is quite poor and addition of ammonium sulfate to AC medium has no effect on growth except to prolong the exponential phase. While cystine clearly acts almost solely as a growth factor, the arginine at least must be used as a nitrogen source in AC medium. Exogenous ammonium typically represses the utilization of alternative nitrogen sources; it also typically is the nitrogen source that gives most rapid growth. In neither case is this entirely true for *C. violaceum*. Ammonium does, however, repress nitrate reduction in *C. violaceum*. Nitrate stimulates the initial growth rate in AC medium, however.

An attractive method for the selection of mutants derepressed for nitrate reduction, or other ammonia-repressible functions, is the use of the ammonia analog, methylamine.[29] Methylamine is ordinarily metabolized slowly or not at all, but is enough like ammonia structurally to still act as a repressor. Thus, when cells are grown in the presence of a non-ammonia nitrogen source plus methylamine (100 mM), only derepressed mutants can utilize the nitrogen starvation.

C. violaceum, however, can metabolize methylamine and grow at a rate equivalent to that seen for ammonia. Higher analogs, such as ethylamine and dimethylamine, may prove to be effective in *C. violaceum*. This approach is now being studied.

Physical/Chemical Modifications

Although pathogen reduction is the primary force behind irradiation of sludge, it is important to be aware of physical and chemical changes which may improve sludge handling or disposal properties. These include filterability, settlability, and odor modifications.

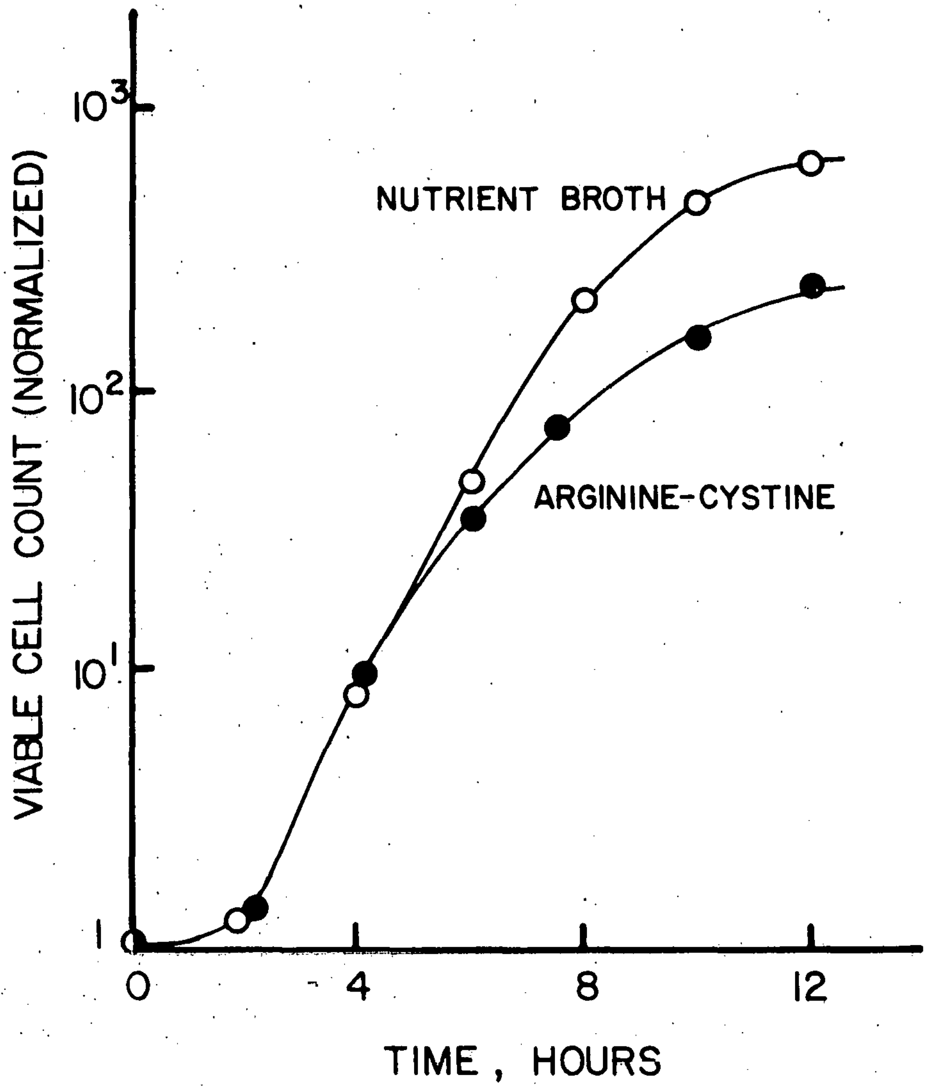

Figure 13. Growth of Chromobacterium violaceum.

Filterability

As much as a ten-fold decrease in specific resistance can be realized under optimum thermoradiation conditions.[33] In a practical application, however, this is not a significant change. Specific resistance plots normally cover several orders of magnitude (are made on a "log" scale), and polyelectrolytes typically cause a hundred-fold to a thousand-fold decrease. Additionally, there appears to be no synergism associated with irradiation and polymer use, so that a process involving ionizing radiation is not expected to offset polymer cost significantly.

Settlability

Although different physical properties of sludge are involved in its settlability rate, centrifugation studies have given results similar to those of filterability. Namely, although there is an initial enhancement in settling properties following irradiation, this change is insignificant when compared to the effect of adding a small amount of polymer.

Odor

Although no measurements have been made on sludges irradiated at ambient temperature, thermoradiation (1 Mrad at 55 C) appears to cause a slight worsening in the odor of liquid digested sludge from the Albuquerque plants.

Summarizing, the changes in filterability and settlability are not significant when compared to polymer addition, nor is the combined effect synergistic. The odor of liquid digested sludge does not improve with thermoradiation, and may, in fact, be somewhat worse.

Dried Sludge Irradiator

An experimental irradiator for treatment of dried sludges is being fabricated and will be installed at Sandia Laboratories in Albuquerque. The system uses a collapsing chain conveyor built by Gough Econ, Staffordshire, England, to optimize the efficiency of the cesium-137 source being used (Figure 14). The chain collapses in three areas, the loading area and above and below the source plaque. The Waste Encapsulation and Storage Facility (WESF) capsules will be used. The facility will initially be charged with approximately 1 megacurie of cesium-137. Throughput capabilities will be eight (8) tons per day at a one megarad dose. Reduced doses will increase throughput linearly.

The conveyor system has been delivered and accepted. Architectural and engineering work is almost completed, and construction is planned for completion by 1 February 1978. The installation of the conveyor, fueling, and checkout will be completed by April 1978. Both composted and dried raw sludges will be treated to determine the dose parameters needed for satisfactory pathogen reduction. The facility will handle both bulk and bagged sludges for radiation processing.

Summary

The Sandia Beneficial Uses Program is attacking the isotope and sludge utilization problem on many fronts. We believe we are being responsive to the various programmatic research needs which, when resolved, will lead to a successful sludge utilization program which is in the national interest by being cost effective, resource and energy conservative, socially acceptable and technically reasonable. Such results would provide another option to the cities burdened by the sludge problem and could potentially provide a cost reduction in their waste treatment programs while recycling a valuable resource for food production.

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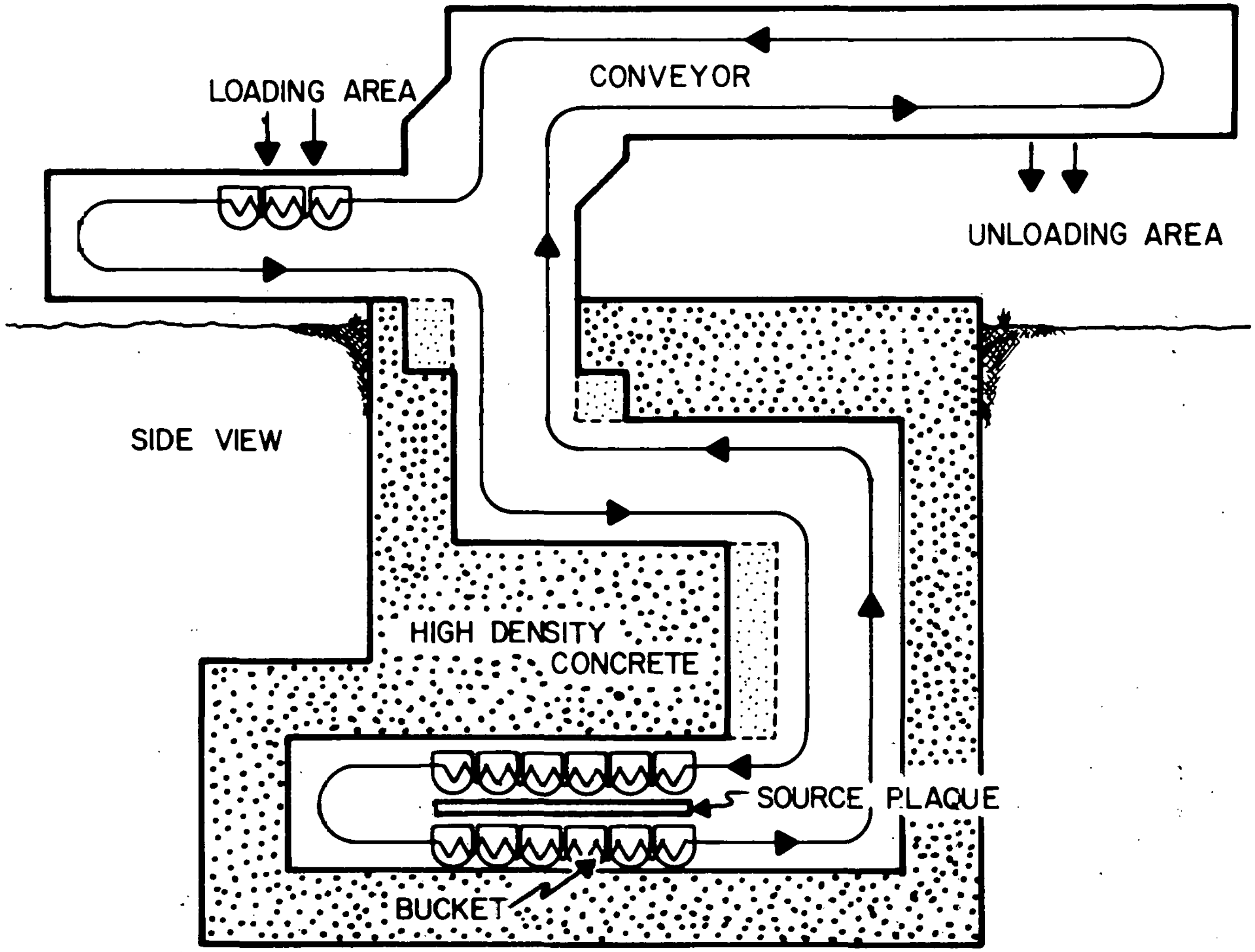

Figure 14. Experimental irradiator for treatment of dried sludges.

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