

Biological Effects of Ocean Disposal of Solid Waste

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**Marine Experiment Station
Graduate School of Oceanography**



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Preface

This is the final report to the New England Regional Commission on a one-year research project on the biological effects of ocean disposal of solid waste.

The problem area is extremely large, involving virtually all oceanographic disciplines. In many areas literature review or limited laboratory experiments had to serve where more detailed work may have been desirable.

The greatest value of this work may be the identification and definition of problem areas. Since resources to study the consequences of ocean disposal are limited, it is important to identify these aspects which are of greatest ecological concern and which are amenable to field and laboratory research.

The laboratory work reported on here was completed in August, 1972. Since that time research on ocean disposal of solid waste has been carried out by G. T. Rowe (Woods Hole Oceanographic Institution) and T. C. Loder (University of New Hampshire), both supported in part by the New England Regional Commission. The emphasis of these

projects has been on field observations at both shallow and deep sites and therefore will complement and extend the conclusions from this work.

Support has been requested for research at the Graduate School of Oceanography to supplement the present work. The areas which have been chosen for emphasis include: (1) oxygen uptake and hydrogen sulfide and ammonia production in waste deposits, (2) effects of hydrogen sulfide on the behavior of motile animals, (3) identification of microflora on waste surfaces.

Contributors to this report include: S. D. Pratt, general direction of research and author of chapters I, II, III, V, VI; A. G. Gaines, research on gas production and author of chapter IV; J. E. Krout, laboratory analyses of eluates and interstitial solutions, and aid in preparation of chapter III; R. Jayne, literature review of metal mobility (Table III-5) and response of benthic animals to chemical substances (Table VI-5); S. Hale, literature review of nutrients in interstitial water (Table III-4); S. B. Saila, director of the Marine Experiment Station.

I. Introduction, Summary and Conclusions

Introduction

Ocean dumping has been identified as an option for the disposal of both residential solid waste and incinerator residue for New England coastal cities (New England Regional Commission Solid Waste Proposal II).

Devanney *et al.* (1970) have examined the economic aspects of ocean disposal of solid wastes. Table I-1 from their report summarizes the costs of various disposal methods for New York City.

Table I-1. Unit cost of various disposal methods based on NYC labor, land, and construction costs; 8% interest rate; and \$1.00 packaging cost. (From Devanney *et al.*, 1970) Collection costs averaged \$28 a ton in New York in 1968, but may average \$18 a ton nation-wide (Council on Environmental Quality, 1970).

Method	Cost per Ton
A. Land-based	
1. 50-mile rail haul; inland sanitary landfill	\$ 7.62
2. incineration	11.00
B. Sea-based	
1. dumping compacted bales	
a) 80-mile ocean tow (bales packaged)	8.09
b) 50-mile rail haul to coast; 80-mile ocean tow (bales packaged)	12.02
2. dumping incinerator residue	
a) incinerator on land	11.96
b) incinerator waterborne	12.00

They concluded that inland sanitary landfill would be little more expensive than disposal at sea, but that such arrangements would be difficult under present political organization. Incineration was found to be expensive whether land- or sea-based. On a basis of "non-ecological" costs ocean dumping was found to be an attractive alternative. The authors predicted that there would be considerable pressure to dump at sea in the near future. Although recycling was identified as a desirable method of disposal, they did not include it in their economic analysis. It appeared that high processing costs and weakness in markets for output would prevent rapid development of recycling.

Devanney *et al.* (1970) discuss two contrasting views concerning ocean dumping and the methods of disposal each engenders. The first is that the ocean is a link in the natural cycle of materials and that organic material should be dispersed in shal-

low waters where mineralization will be most rapid. The other is that wastes are potentially harmful and should be segregated from natural cycles by minimizing dispersion and dumping them in physically and biologically inactive areas. These alternative methods have been discussed in terms of dredge spoil disposal by Andreliunas and Hard (1972). Segregation was assumed desirable in a report on deep ocean dumping of baled refuse prepared by the National Industrial Pollution Control Council (1971).

Our research project was based on the assumption that containment would be a necessary part of any disposal plan. The problem of floating debris and uncertainty about the concentrations, biological effects, and rates of degradation of waste constituents all argue for containment.

The ocean has been used as the ultimate disposal site for a variety of waste products. At first glance, solid waste would seem to be among the least desirable of these. The Council on Environmental Quality (1970) has recommended that "Ocean dumping of existing sources of solid waste would be stopped as soon as possible and no new sources should be allowed." They also suggest, however, that research be carried out on subjects related to ocean disposal, including pathways of waste materials and the effects and longevity of toxic materials in the sea.

The research discussed in this report attempts to answer the question of the ecological cost of ocean dumping of compressed residential solid waste. Solid waste in compact blocks has very different properties than either dispersed solid waste or other waste products. It is therefore necessary to study this form of waste to determine if it is indeed an undesirable material for ocean disposal.

During the course of these investigations, numerous reports were reviewed dealing with the management of sanitary landfills. It is clear that ground water pollution by leachates will continue to be a problem in the eastern United States. Proposed collection and treatment of these leachates will make landfills more complex and expensive. An important feature of ocean dumping is that it circumvents this problem. Furthermore, total quantity of substances eluted from waste may be less in the ocean than in land disposal.

Both field and laboratory studies are necessary to determine the consequences of ocean disposal of

solid waste. This report is based exclusively on laboratory studies, although "type" disposal locations were considered as a basis for the projection of results to the marine environment.

The contracted objectives of this project were to determine the following properties of compacted solid waste:

1. The exudation of dissolved materials and their effects on the physiology and behavior of marine life.
2. The loss of solid material and its dispersal characteristics.
3. The interactions of fouling organisms and waste blocks.
4. The interactions of motile animals (such as fish and lobsters) and waste blocks.

A variety of procedures were used in attempting to make these determinations. Scaling down waste blocks was an important problem in the design of these experiments. The heterogeneity and large size of the constituents of solid waste make it difficult to obtain small representative subsamples. Because of limited space and pump capacity, it was necessary to reach a compromise by using a few large tanks and a larger number of small ones. Both flow-through and batch tanks were used.

A series of analyses of gases produced by waste were undertaken when it was observed that gas formation was occurring in all experimental tanks.

Summary

Laboratory and literature research was carried out on a variety of topics related to ocean disposal. A summary of experiments, results, and projections for each major area follows. Some general conclusions concerning ocean disposal are given separately.

General Methodology

It was assumed that material to be disposed of would be residential solid waste and that shredding and compaction would precede dumping.

The characteristics of three "type" disposal areas in the New England area were briefly considered as a basis for the design of experiments and for the projection of experimental results. The areas included a shallow shelf station off southern New England, a basin in the Gulf of Maine, and the con-

tinental slope and rise off New England. Shallow areas are better known biologically and more easily monitored than deep areas, although they are close to fishing grounds. There is some evidence of active currents in the slope areas. Although the benthic environment of deep areas of the Gulf of Maine is not well known, this area merits further consideration on the basis of physical isolation.

Test waste was prepared containing milled paper, "food", tin cans, aluminum, plastic, and glass. The percentage of paper (72%) was higher than in typical wastes.

A number of different observations were carried out in a large flume (16' x 1' x 1') floored with test waste and a control flume floored with sand. A continuous flow of unfiltered seawater was provided in these tanks. Oxygen uptake was studied in smaller flumes (4' x 4" x 4") and waste degradation was monitored in 20-gallon tanks in a temperature controlled bath at 9°C.

Interstitial Solutions and Eluates

A variety of dissolved substances were monitored in water overlying waste and in interstitial water. It was possible to detect dissolved organic carbon, carbohydrates and organic nitrogen in the waste eluate for only a few days after placement of the deposit.

Interstitial solutions were monitored in the large flume and in closed tanks. The tanks contained: (1) high organic matter waste in salt water, (2) high organic waste in fresh water, (3) high organic waste in salt water poisoned with mercuric chloride and (4) low organic waste in salt water.

The same general pattern of chemical changes was found in the interstitial solutions of all biologically active saltwater deposits. There was an immediate drop in pH due to constituents in the paper. Oxygen was consumed in 6-8 days. Hydrogen sulfide (H₂S) was produced after about 50 days and continued to increase in concentration throughout the experiment. Dissolved iron concentration was initially high, but decreased to low values after H₂S production began. Nitrate disappeared at the same time as oxygen. Ammonia concentrations were variable and reached values of 20 to 82 mg/l after 80 days in high organic matter waste. Phosphate reached a concentration of 22-32 mg/l after 50-60 days and then leveled off. Although carbohydrates

decreased to low values, total dissolved organic carbon remained high at the end of 80 days. Turbidity of interstitial solutions increased through time. Variation in duplicate samples taken from single tanks indicated that rates of degradation and quality of degradation products were spatially heterogeneous.

Although temperature and pressure will limit the rate of degradation at an ocean disposal site, waste deposits will become anoxic and will contain H_2S . H_2S will remain high as long as degradable organic matter remains.

The only toxic substance other than H_2S which was measured was ammonia which reached toxic concentrations in interstitial waters. Volatile fermentation products which were not identified could have toxic effects on infauna or behavioral effects on motile animals.

Ammonia levels in the interstitial water of wastes were near those in highly organic natural sediments but phosphate levels were much higher, possibly due to relatively limited adsorptive surface. Diffusion of these nutrients would argue against disposal in shallow areas with restricted circulation.

In order to model the transfer of dissolved substances from waste deposits, it will be necessary to estimate diffusion coefficients. As a first attempt to describe the bulk properties of compressed waste, permeability was measured in test waste with varying densities. The waste was extremely impermeable at densities near those that would be used in actual dumping.

Solid waste contains many toxic metals. An important consideration in proposing ocean disposal is the mobility of these metals in anoxic environments. A review of the literature indicates that several toxic metals (including copper, chromium, mercury, and zinc) form insoluble sulfides in the presence of H_2S . Other experiments, however, have demonstrated the occurrence of these metals in soluble forms in anoxic organic sediments. There is a clear need for more laboratory research in this area.

Gas production in solid waste

Model solid waste beds and slurries suspended in seawater were analyzed for gaseous content. At various stages of decomposition, H_2 , O_2 , N_2 , CH_4 , CO_2 , and H_2S were detected. Initial gas production

activity evolved large amounts of H_2 ; later CH_4 and H_2S were produced in lesser quantities.

In shallow water interstitial bubble formation is likely with associated buoyancy and ejection of pore water. In deeper water the possibility of bubble formation, especially involving H_2 and CH_4 , should not be discounted.

Highly toxic levels of H_2S were characteristic of interstitial water. The possibility of rapid release of this water is a matter which should receive attention in baling considerations and dump site selection.

Oxygen uptake by solid waste

Oxygen uptake was measured in both large and small flumes on waste which had been held in flowing seawater at ambient temperatures for periods of up to four months. During these experiments a volume of water was sealed in each flume, mixed by pumping, and the oxygen concentration measured with an oxygen electrode.

The rate of oxygen uptake was several times higher in the waste than in a control flume floored with sand. These rates were higher than those of most natural infaunal communities measured at similar temperatures. Uptake never exceeded 100 ml/m²/hr, however. Examination of the literature suggests that diffusion rates of oxygen and reduced compounds limit oxygen uptake regardless of organic matter content.

Since these rates are orders of magnitude lower than rates of dispersion in aquatic environments there will be reduced likelihood of low oxygen levels or toxic H_2S levels in overlying water other than in the boundary layer in contact with a waste deposit.

Reactions of organisms to waste deposits

A number of interrelated phenomena were observed in flowing seawater systems containing solid waste.

A succession of microbial films developed on the waste surfaces. Eventually sulfide oxidizing genera dominated these films.

Fouling experiments were somewhat unsuccessful because fouling was limited in both waste and control flumes. The slides in the waste tank were fouled by filaments of sulfide bacteria. Nematodes, oligochaetes and harpacticoid copepods were found

among these filaments. These groups are resistant to oxygen depletion and the presence of H₂S.

Only two large infaunal species successfully colonized waste deposits. *Capitella capitata*, an indicator species in organically polluted areas, was found in very high densities in a tank with measurable H₂S in the overlying water. *Nereis succinea* colonized the large flume, burrowing into waste containing very high levels of H₂S (nearly 400 mg/l).

Animals were screened for sensitivity to waste eluate by 72-hour bioassays in eluate flowing very slowly over a large surface area of waste. The most sensitive species tested was a marine fish. The only invertebrate suffering mortality was a shrimp. No mortality occurred in barnacles, hermit crabs, rock crabs, mussels, surf clams, or ocean quahogs. The crustacea were heavily fouled by bacteria and may eventually have died from restrictions of respiratory and feeding movements. The major source of toxicity in the eluate appeared to be H₂S.

The eluate did not stimulate feeding responses in three decapod species tested. It is believed that substances normally responsible for attracting scavengers to food were absent from the eluate.

The following projections were made concerning the effect of waste on organisms in the marine environment:

1. Only infaunal species tolerant to low oxygen levels and the presence of H₂S will colonize the waste.

2. Both infauna and epifauna will be limited if the oxygen in the overlying water falls below 2 ml/l. This will be a function of rate of oxygen uptake; waste surface area; and the oxygen content, velocity and turbulence of overlying water.

3. The effect of H₂S on epifauna and motile animals will depend on the dispersion rate in the overlying water. H₂S will be present in waters downstream from the dump site but little information is available on its attraction or repulsion of motile animals.

4. Newly deposited waste will attract scavengers; however, this attraction may be diminished after a period of months.

5. Fouling of the deposit may be restricted to species resistant to H₂S. Little fouling will occur in deep waters regardless of the deposit surface

environment. It is not possible to state whether wood boring species will be attracted to waste.

6. Bacteria on the waste surface may provide food for deep sea animals.

General Conclusions

In the preceding summary, conclusions were developed concerning a variety of characteristics of solid waste in relation to various environments and animal types. More general statements are made here.

It seems too early to categorically condone or condemn ocean dumping of solid waste. It is likely that this decision will be made on other than scientific grounds. The possibility of increased concentrations of unsightly floating particles may be an important factor. See Carpenter and Smith (1972) and Horn *et al.* (1970) for reports on the presence of plastic particles and oil lumps on the sea surface.

It is also too early to choose a disposal site or sites for the New England region. Various investigators still have entirely different concepts of the type of dump most desirable. Some are considering the deep sea while others would prefer to build fishing reefs in shallow water.

There is no question that the decomposition of solid waste will be slow. At this time it is impossible to make even an order of magnitude estimate on the longevity of a massive waste deposit.

Metal corrosion rates from deep-sea test exposures have been used by the National Industrial Pollution Control Council (1971) and Arthur D. Little, Inc. (1973) to model corrosion from waste bales. These models, however, do not take account of accelerated corrosion of metals penetrating an oxidation-reduction discontinuity at the waste surface or of possible very slow corrosion rates within anoxic deposits.

Jannasch (1970) states that "the relative low rates of microbial activity found at deep water conditions seem to render this kind of waste disposal rather inefficient" and that "accumulation in an uncontrollable situation may involve the danger of drifting waste or intermediate decomposition products by bottom currents." This "inefficiency" presumably refers to a slow rate of conversion of organic matter to dissolved substances.

Since prevention of erosion and transport of

waste would be a prerequisite to any dumping plan, a slow breakdown rate need not be undesirable. As Jannasch (1970) states, "The ratio between rates of oxygen supply and microbial activities will decide whether a deep sea fauna of bottom animals will participate in the enrichment or whether anaerobic conditions will arise eliminating benthic populations of the non-microbial fauna." The effects of H_2S and ammonia produced in a waste deposit will also depend on the rates of production relative to diffusion from the waste and dispersion in the overlying water. Thus the reduced rates of degradation in deep waters reported by Jannasch (1970), Jannasch *et al.* (1971) and Wirsen and Jannasch (1972) will reduce the possibilities of local disturbance.

Different characteristics of waste deposits are of importance in considering short- and long-term environmental effects. Over the short term it is necessary to know the effect of waste on the benthic species and fisheries of the immediate area.

The experiments reported on here suggest that only species resistant to low oxygen and H_2S would burrow into a waste deposit. Colonization by epifauna would depend on the current velocities at the dump site. To predict short term effects more information is needed on the production, diffusion, and oxidation rates and toxicity of H_2S . Information is also needed on the ecological and physical characteristics of potential disposal sites. Potential sites such as the deep basins of the Gulf of Maine have not been well studied to date.

The most important long term effects to consider at this time appear to be the worldwide levels of toxic metals, plant nutrients, and organic pollutants that would result from ocean disposal as compared with other disposal techniques. Although these questions are beyond the scope of this report, it is hoped that the description of the internal environment of a waste deposit provided here will stimulate interest in such comparisons. The problem of pollutant mobility and diagenesis in organic deposits also merits special attention.

It may be appropriate to mention that several

recent studies of metals in the marine environment have shown that physiological regulation may be more important than bioaccumulation. An interesting example is Knauer and Martin (1973) who found no evidence of food chain amplification of mercury in a pelagic food chain. This type of study is essential in separating actual environmental hazards from "potential hazards."

The deep sea fauna includes a surprisingly large number of small deposit-feeding species. Sanders (1968) has hypothesized that this is made possible by a high degree of biological accommodation between species in an unvarying environment. A corollary of this hypothesis is that any sudden change in this environment would harm both individuals and communities. Bretsky (1968) and others have emphasized that there will be little selection for genetic or physiological flexibility in such an environment. If this sensitivity is verified, attention would have to be given to control of constituents, effective wrapping, and minimization of waste surface area.

Dayton and Hessler's (1971) discussion on the role of large mobile scavengers in consuming and dispersing large particles of food in the deep sea does not argue against the sensitivity of deep-sea benthic communities, but it does indicate an ability of that community to assimilate large masses of food.

The experiments carried out during this project help to picture the sea floor at the site of an ocean dump. Although the bottom at the actual dump site will be degraded, the effects of oxygen consumption and H_2S production will probably not affect a wide area. These short term effects do not appear to be reason for denying the use of the sea floor for disposal of residential solid waste.

Long term effects of metals and persistent organic compounds must be examined further, however, before pilot-level dumping is implemented on the continental shelves and in shelf basins. The sensitivity of deep-sea fauna to disturbance must be determined before deep water dumping is considered.

II. General Methodology

Assumed Disposal Technique

The following assumptions have been made concerning the physical form of the solid waste and the dumping techniques which may be employed. These were necessary in designing experiments and as a basis for projecting results.

1. Source of the waste is residential; no industrial waste is included.
2. The waste is shredded, compressed and baled to achieve high density.
3. Bale size is as large as practical and still allow high densities. Blocks 3-4 feet on an edge have been suggested.
4. Wrapping with perforated plastic is likely in order to retain loose surface material.
5. Bale weight in seawater is 100-300 pounds.
6. Bale weight increases during sinking due to compression and expression of air.

Other elements have been considered which are not presently determined. These variables include: (1) depth of water and resulting pressure, (2) strength and longevity of wrapping material, (3) distribution of bales on the sea floor, (4) sedimentation rate at the dump site, and (5) changes in solid waste make-up due to recycling of some materials.

Type Disposal Areas

Three ocean sites have been chosen as a basis for projection of laboratory results to the behavior and effects of solid waste on the sea floor. These type-areas have contrasting characteristics. They are not being proposed as disposal sites, although each has been suggested as a site for various materials by other authors. The areas are shown in figure II-1.

Southern New England Continental Shelf

Saila, Pratt and Polgar (1972) suggested that a dredge spoil disposal site could be established on the southern New England shelf at a depth of 80 meters. This area is approximately 50 miles from the mouths of Narragansett Bay and Long Island Sound.

Bottom sediments are silts and clays which were deposited during a lower stand of sea level (Garrison and McMaster, 1966). Present currents are apparently below the critical velocity necessary to

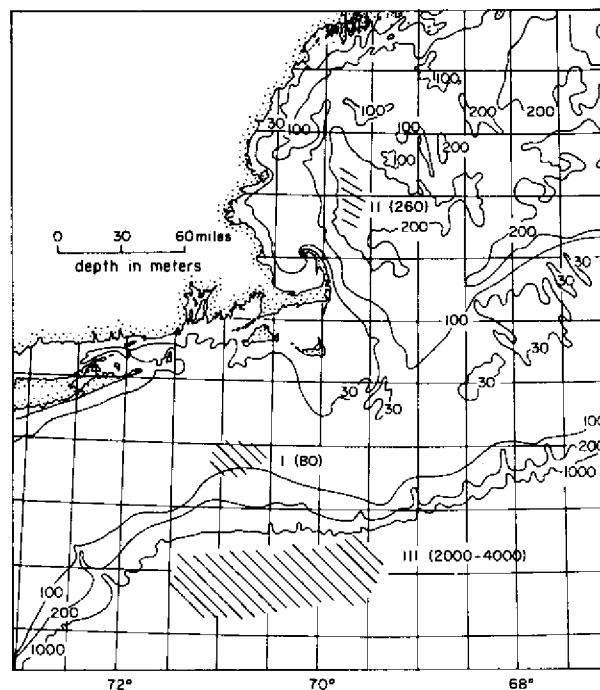


Figure II-1. Location of type disposal areas in the New England region.

initiate erosion. (The minimum velocity capable of eroding fine sand is between 15 and 30 cm/sec.) Lack of recent deposition in this area may reflect low sediment loads and moderate tidal and wave induced currents.

Although wave-induced bottom current velocities at 80 meters are considerably reduced relative to surface values, some resuspension probably takes place during the passage of large waves. McClenen (1973) calculated that velocities of 15 cm/sec and over would be expected 2.3% of the time at 74 meters based on waves reported between 35-40N and 70-75W.

Bumpus (1965) indicated that non-tidal drift is shoreward over the inner two-thirds of the southern New England shelf. Bumpus (1973) gives the drift rate in this area as 0.7 ± 0.2 nautical miles/day.

Bottom temperatures in the area are between 5 and 12°C (Bigelow, 1933; Wigley and McIntyre, 1964; Walford and Wicklund, 1968; Chamberlin and Stearns, 1963). January through September the temperature falls between 7.5 and 10°C; higher temperatures are recorded in November and December. These relatively high temperatures throughout the year are a result of Gulf Stream influence.

Oxygen is probably near saturation values in these relatively shallow and well mixed waters.

Wigley and McIntyre (1964) sampled this area at depths of 69-99 meters. They found large numbers of mollusks (200-500/m², mostly bivalves), brittle stars (100-700/m²) and polychaetes. Samples taken by Sanders, Hessler and Hampson (1965) at 97m are also representative. Of 5314 individuals/m² they found 41% polychaetes, 23% brittle stars, 19% bivalves, 5.5% coelenterates, and 3.4% crustaceans.

The present commercial fishery yield from this area is low in contrast to that of inshore trawling grounds and shelf-edge lobster grounds (National Marine Fisheries Service, 1970). The low abundance of crustaceans may limit ground fish populations. Mid-shelf concentrations of some species (butterfish, silver hake) have been mapped in this area in autumn on the basis of exploratory fishing (Fritz, 1965).

Although deep ocean sites are now receiving emphasis for disposal of solid waste, shallow sites offer several potential advantages over deeper areas.

These include: (1) dollar savings in equipment and time, (2) reduced probability of forced dumping during storms, (3) improved control of vessel positioning and waste placement, (4) relative ease of monitoring of waste on the bottom, and (5) use of modified bottom for attracting fish.

Decomposition can be expected to take place more rapidly on the shelf than in deeper, cooler waters. An hypothesis can be made that the benthic animals found on the shelf will be more capable of dealing with the stress of habitat modification than those of the physically stable deep sea.

Major disadvantages of shelf disposal sites include: (1) less waste compaction by hydrostatic pressure, (2) competing uses of the area for fisheries and recreation, (3) possible erosive wave-induced bottom currents, and (4) inshore bottom current drift and inshore summer wind direction.

Basins of the Gulf of Maine

The closed basins in Massachusetts Bay and the Gulf of Maine are being considered as disposal sites for New England coastal cities. First (1972) has considered Stellwagon Basin, 25 miles from Boston as a site for disposal of incinerator ash. Anderson, Tishler and Blanchard (1971) are ex-

amining Jeffreys Basin, 15 miles from Portsmouth, New Hampshire, as a site for solid waste disposal. The Wilkinson-Murray Basin, about 60 miles from Boston, is of special interest because of its great depth. It has been suggested as a disposal site by Rowe (1971). This basin is closed below 200 meters and has extensive area below 260 meters.

No wave effects are felt at these depths and non-tidal circulation is probably sluggish. Tidal currents (5-10 cm/sec) are probably the dominant source of dispersing energy.

The sediments of the basin are silts and clays supplied by reworking of surrounding shallow banks and ridges (Ross, 1970). Land-derived sediments appear to be deposited in near-shore basins. Suspended sediment load increases exponentially from 50 meters to the bottom (Spenser and Sachs, 1970). This material is resuspended sediment with low organic content.

The emphasis of the quantitative studies on benthic animals in the Gulf of Maine has been on sand and gravel bottoms supporting important fisheries. These studies suggest that muddy basins have lower species diversity and standing crops of bottom animals than gravel, sandy, and silty sand bottoms. A specialized fauna of deposit-feeding species is found on muddy bottoms. These include heart urchins, brittle stars, mud stars, scaphopods (tusk shells), specialized amphipods and isopods, and polychaete worms (Wigley, 1968). Presumably this faunal assemblage has low value as fish food.

Maps of fish abundance (Fritz, 1965; Wigley, 1965) show that the important food fish (haddock, cod, hake species, and red fish) are largely absent from the Wilkinson-Murray Basin. This is a function of sediment type and food availability rather than temperature or depth.

The Wilkinson-Murray Basin offers several advantages as a solid waste disposal site. These include high hydrostatic pressures, protection from wave-induced currents, low fishery utilization, and closeness to land.

Possible disadvantages include the possibilities of interference with surrounding fisheries or presently undeveloped fisheries in the basin and oxygen depletion in the basin because of low exchange rates.

New England Continental Slope and Rise

The continental slope is about 90 miles from

New York, Long Island Sound and Narragansett Bay. At the foot of the slope the continental rise extends from 50 to 100 miles further at depths of 2000-4000 meters. The National Industrial Pollution Control Council (1971) discussed a hypothetical disposal area at a depth of 2300 meters beyond the edge of the New England shelf. A slope site 1800 meters deep has been proposed by Rowe (1971) for experiments on solid waste disposal.

Although bottom currents at the above site are only 0.25-0.5 cm/sec (Smith and Teal, 1973), currents on the slope and rise are not necessarily of low velocity. Heezen and Hollister (1964) and Zimmerman (1971) have identified a western boundary undercurrent flowing southwest along the contours in interaction with the Gulf Stream. Zimmerman (1971) recorded "geologically significant" velocities (15-20 cm/sec) at several stations for 1-14% of the period recorded. The maximum velocity recorded over a 24-day period was 26.5 cm/sec. These currents probably could not resuspend sediment other than fine unconsolidated sand, but they could transport a wide range of materials already in suspension. Bottom photographs (Heezen and Hollister, 1964) show transverse ripples in sand on the upper rise, and longitudinal forms parallel to the current flow in finer sediments on the lower rise.

Trumbull and McCamis (1967) and Dillon and Zimmerman (1970) examined New England submarine canyons by submersible and found weak but consistent downflowing currents. It appeared that "biological erosion" by the activities of fish and crabs was more significant than postulated catastrophic currents in sediment movements down canyons. Although coarse sediments reach the slope and rise from slumping and turbidity currents, much of the sediment consists of fine salts, clays and the remains of planktonic plants and animals.

Sanders, Hessler and Hampson (1965) and Sanders and Hessler (1969) have reported on the benthos of the slope and rise. A distinct break in species composition is found at the edge of the shelf. This is ascribed to differences in seasonal temperature variation. A 10°C range at 98-meters depth on the slope diminishes to a 1.4°C range at 487 meters. Below this, the temperature is 4-5°C year round. Oxygen concentrations are not limiting in this area. In the northwest Atlantic, oxygen levels are 6 ml/l below a 4.0 ml/l oxygen minimum layer at 100-500 meters (Riley, 1951). Sanders and Hess-

ler report that the density of animals is reduced on the slope and rise by a factor of 26: 220 from that of the shelf. Abundance of food can be assumed to control density and biomass on the slope and rise rather than oxygen concentration, sediment parameters or temperature.

Advantages on the use of the slope and rise as a disposal site include high hydrostatic pressures and the absence of uses by man. Disadvantages include the difficulty of positioning for both dumping and monitoring, and the unknown consequences of introducing pollutants into a little known environment occupied by stenotopic animals (adapted to an unchanging environment).

Test Materials

In the proposal describing this research it was stated that test solid waste would be obtained from either private firms or government agencies. A decision was subsequently made to prove these studies without communication with private interests. After the Chief of the Ultimate Disposal Branch (Division of Research Development, Solid Waste Management Office) indicated that no "standard" shredded or ground solid waste was obtainable at that time, a solid waste formula was determined and test material was made up for these experiments.

Although the composition of actual solid waste is highly variable, it is clear that the use of a standard artificial mixture would allow better correlation between the results of various studies on degradation and leachate production.

The highly variable nature of residential solid waste is well known. The composition of waste varies with location and season. Most constituent analyses place waste into a number of categories. Kaiser (1966) used 27 categories (Table II-1) but Hickman (1968) found that 8 categories were sufficient for all practical purposes. Recent attention has been given to sampling technique (Klee and Carruth, 1970) and proximate analysis (moisture, volatile matter, noncombustible, etc.) and ultimate analysis (moisture, carbon, oxygen, nitrogen, etc.) (Susag, 1970; D. Wilson, M.I.T., pers. comm.). These analytic techniques are especially important to incinerator operations. Ultimate analysis can provide maximal values of nutrient and toxic ele-

Table II-1. Composition of residential solid waste (% by weight).

Fungaroli and Steiner (1971) from Kaiser (1966)		Drobay, Hall and Testin (1971)	
Corrugated paper boxes	23.38	Paper	55
Newspapers	9.40	Newsprint	12
Magazine paper	6.80	Cardboard	11
Brown paper	5.57	Other	32
Mail	2.75	Metallics	9
Paper food cartons	2.06	Ferrous	7.5
Tissue paper	1.98	Non-ferrous	1.5
Plastic-coated paper	0.76	Glass	9
Wax cartons	0.76	Food wastes	14
Vegetable food wastes	2.29	Yard wastes	5
Citrus rinds and seeds	1.53	Wood	4
Meat scraps, cooked	2.29	Plastics	1
Fried fats	2.29	Miscellaneous	3
Wood	2.29	Moisture	30%
Ripe tree leaves	2.29		
Flower garden plants	1.53		
Lawn grass, green	1.53		
Evergreens	1.53		
Plastics	0.76		
Rags	0.76		
Leather goods	0.38		
Rubber composition	0.38		
Paints and oils	0.76		
Vacuum cleaner catch	0.76		
Dirt	1.53		
Metals	6.86		
Glass, ceramics ash	7.73		
Adjusted moisture	9.05		

Council on Environmental Quality (1970)	
Paper products	43.8
Food wastes	18.2
Metals	9.1
Glass and ceramics	9.0
Garden wastes	7.0
Rock, dirt, ash	3.7
Plastic, rubber, leather	3.1
Textiles	2.7
Wood	2.5

ments added to the marine system. Identification of waste by component is necessary to predict short term effects because of the great variation in degradability between various organic materials.

Projections have been made as to the composition of wastes in the future (Niessen and Chansky, 1970). Bulk density water content and food content will decrease while the content of paper, cardboard, and plastic will increase. Metal and glass content will stay approximately the same. These trends are evident in other developed countries (*Refuse Removal Journal*, 1967). Recycling and restrictions on plastic or non-returnable containers (*Chemical and Engineering News*, 1971) will probably not change these projections.

When large volumes of experimental waste are used, it is possible to include many components. Fungaroli and Steiner (1971) used all 27 components listed by Kaiser (1966) when they set up a large lysometer. It is not possible to provide representative samples of such a mixture for small experiments.

A simplified formula was used in these experiments (Table II-2). Multiple sources of cellulose and easily degraded organic matter were represented by a paper mixture and a food mixture. It was considered desirable to exclude such biologically active substances as paints, solvents, and heavy metals until the details of degradation of the basic components were known.

Table II-2. Composition of test waste used in this study.

Component	Mix A	High Food	Low Food
Paper	72.8	71.7	72.5
Food*	4.9	9.8	2.2
Tin plate	7.2	7.0	7.0
Aluminum foil	0.7	0.6	0.7
Glass	11.5	9.8	16.5
Plastic	2.8	1.1	1.1

* "Food" contained approximately 23% protein, 7.5% fat, 67% carbohydrate.

Newspapers, magazines, and cardboard were shredded in a Mill Pak hammer mill on loan to

M.I.T. This material is probably more finely divided than actual waste would be. Food components (dry dog food, rice, and sugar) were chosen to allow good dispersal. Tin plate, aluminum foil, and plastic were added as 1-inch squares. Glass was broken and passed through a 1-inch sieve.

"Fresh weight" of this material consisted of about 8% water. In all cases salt water was used as "make up" water in preparing test deposits. This was done to model an actual dumping situation in which seawater would be forced into bales.

Experimental Systems

Both flow-through and closed systems were used in these experiments, the first for studying surface effects and animal interactions and the second for monitoring within-bale degradation processes.

Open systems

Flumes were used in studies of animal colonization and oxygen consumption. This configuration was chosen to provide water velocities approaching those in the natural environment. It was hoped that sedimentation of fine-grained and organic-rich material could be prevented. This is a familiar problem in square or circular tanks. In some cases shallow depths were used to achieve high flow rates. In all cases sunlight was excluded to prevent growth of algae and photosynthetic bacteria. Larger organisms were removed from the seawater by filtration through a 36" x 36" nylon screen with a 0.76 mm mesh.

First observations were made in two small 4" x 6" x 48" glass flumes. A considerable amount of work was carried out in two large flumes (Figure II-2) constructed during the summer of 1971. These had an area 10' x 1' for placement of a bottom deposit. "Tank 1" was floored with solid waste. "Tank 2" was floored with natural sediments and served as a control. These flumes had flow collimators, entrance and exit aprons, and could be fitted with glass covers. The waste flume had an observation window and tubes for sampling interstitial water. Inlet pipes were of large diameter so that water velocities could be increased to high levels for experiments on erosion.

A 16' x 2' flume with shallow water served as a generator of solid waste eluate for bioassays. Each

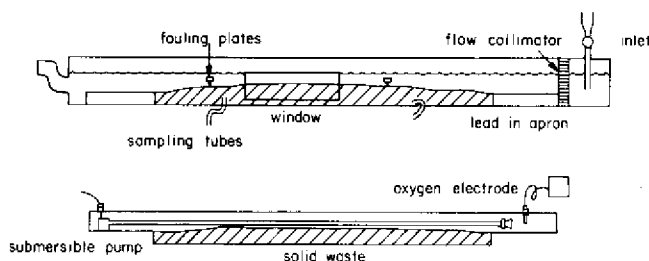


Figure II-2. Cross section of tanks 1 and 2 in flow-through configuration and sealed for oxygen uptake determinations.

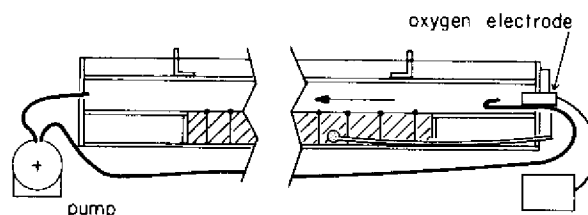


Figure II-3. Cross section of 4' (36" test surface) flume in sealed configuration for oxygen uptake determination.

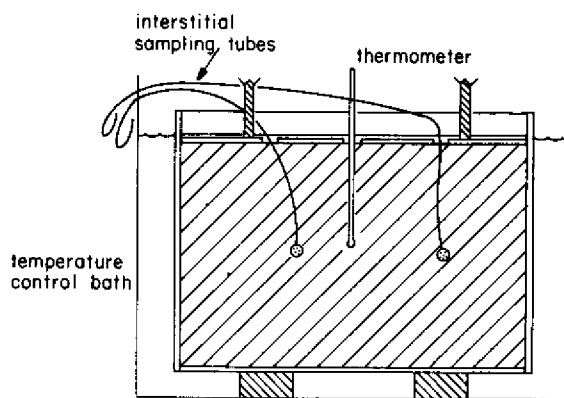


Figure II-4. Cross section of 20-gallon closed tank.

of these large tanks was filled with relatively low density waste (400 lbs/yds).

A series of 8 glass flumes with 4" x 36" of waste surface were constructed for replicated oxygen consumption studies. Each of these was loaded with 3 dense baled waste blocks 12" x 4" x 2" (Figure II-3).

A covered 18' diameter pool was used in making observations on the attraction of scavengers to simulated wrapped bales. These bales consisted of 6" deep trays filled with waste and covered with perforated plastic.

Closed systems

Initial observations indicated that only the immediate surface of waste deposits would be affected by the overlying water. Degradation processes within bales were studied in closed systems in which temperature and other variables could be more carefully controlled.

Four 20-gallon glass tanks were filled with rela-

tively dense 1' x 1' x 2' waste blocks prepared in a threaded rod press. These tanks were equipped with filter stones for sampling interstitial solutions and with loose fitting covers (Figure II-4). They were placed in a temperature control bath at 9°C. Gas generation was studied in the tanks described previously. In addition, 1- and 2-liter glass bottles held at room temperature and at 8°C were utilized.

III. Interstitial Solutions and Eluates

High concentrations of dissolved compounds occur within deposits of water saturated solid waste. The quantity and quality of these change as degradation proceeds. Dissolved compounds may leave the waste by diffusion or through expression of pore water and make up an "eluate" similar to the "leachate" produced by gravity flow through sanitary landfills.

A large number of both organic and inorganic substances occur in interstitial solutions. A limited number of these were chosen for analysis because of their biological significance and the availability of analytic techniques.

Two series of observations are presented here. The first were made on a deposit in an open system with varying temperature (chapter II). Samples were taken at close intervals during November and December, 1971, and additional determinations were made in January, April, June, and August, 1971-72. A second series of observations were made in temperature controlled closed tanks with different levels of reactants.

The related problems of diffusion rates in solid waste and mobility of metals are discussed separately.

Experiments with Waste Deposits

Analytical Methods

The following methods were used in analyses of eluates and interstitial solutions: dissolved organic carbon (Beckman carbonaceous analyser), dissolved carbohydrate (Strickland and Parsons, 1968), nitrate nitrogen (Strickland and Parsons, 1968), dissolved organic nitrogen (Strickland and Parsons, 1968; Solorzano, 1969), reactive phosphate (Johnson, 1971), dissolved oxygen (Carpenter, 1965), low concentrations of hydrogen sulfide (Cline, 1969), high concentrations of hydrogen sulfide (Gaines and Pilon, 1972), and total dissolved iron (Hach Chemical Co., 1971). Temperature and oxygen concentrations were routinely monitored with an oxygen electrode and temperature sensor (Yellow Springs Instrument Co., Model 54). The pH of interstitial water was measured with a Corning Model 10 pH meter, and turbidity with a Hach Turbidometer (Model 1860A).

For each chemical procedure duplicate samples were collected from one port of the experimental flume. A single sample was collected from each of two sample ports in the closed tanks. Samples were taken with a 100 cc Yale hypodermic syringe. A Gelman Leur-lok filter holder was attached to the syringe and the sample slowly pressed through a 25-mm Gelman glass fiber filter. Precombusted filters (450°C, 4 hours) were used for the dissolved carbon samples. Ammonia (NH₃-N) and iron samples were collected in 100 ml serum bottles and analyzed within 1-2 hours of collection. All other samples were stored frozen at -20°C for later analysis. Colorimetric determinations were performed on a Bausch and Lomb 340 spectrophotometer, except for phosphate determinations (Beckman D. U. spectrophotometer). Interstitial water samples with high concentrations of dissolved substances were diluted with deionized water when necessary.

Open System—Description

Tank 1 contained a surface area of .9334 m² of solid waste mix A described in chapter II. The depth of the deposit varied from 10 cm at the end aprons to 23 cm in the central portion (Figure II-2). During the fall of 1971 water depth averaged 11.5 cm and was 7.7 cm in the center portion. Water velocities varied from 0.54-1.11 cm/sec during this period. In February to August 1972 depth over the center portion was reduced to 1.6 cm, increasing the water velocity to about 5.3 cm/sec. Water ran continuously with the exception of several days in February 1971 when the surface froze.

The waste was packed into a form and placed in the tanks in sections. A 1" mesh vinyl-coated screen was used to contain the material and was left on until January 6. The immediate surface of the deposit was disturbed during experiments on erosion resistance January 21.

Pockets of trapped air could be seen through the tank window. These persisted as long as 6 months, presumably with varying gas makeup.

The temperature of the seawater in tank 1 is shown in Figure III-1. This varied over 20°C during a year. Rapid drops of several degrees a day were common during the fall of 1971 but the average weekly temperature fell slowly after an initial drop from 15 to 9°C during the first days of the experiment.

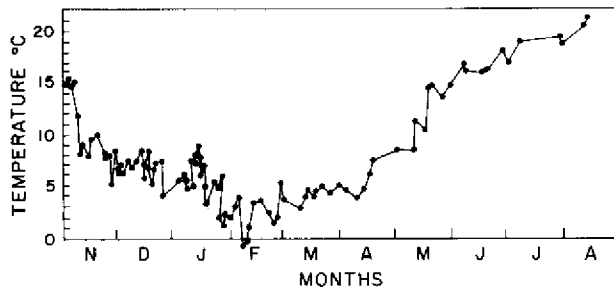


Figure III-1. Water temperature in tank 1 (flow-through) Nov. 1971-Aug. 1972.

Sedimentation of silt size particles and organic detritus was particularly noticeable following storms. The normal deposition rate was 0.6 to 0.3 g dry weight/m²/day at the upstream and downstream ends of the tank.

The control tank (tank 2) was covered with a layer of fine sand collected from a depth of 100 feet in Rhode Island Sound and held dry for several months before use.

Open System—Results

On the first day of the experiment (November 4) significant upstream-downstream differences in concentration of dissolved organic carbon, dissolved carbohydrate, and dissolved organic nitrogen were observed (Table III-1). By day 4 only carbohydrate and dissolved organic carbon were measurable at a flow rate reduced to about 0.2 cm/sec. Carbohydrate made up much of the soluble organic matter in the eluate at this point. In addition, there was a slight tendency for a downstream decrease in dissolved oxygen concentration (0.2-0.4 mg/l) during the first week of the experiment (Table III-2). During the remainder of the fall there were no detectable upstream-downstream differences in any of the observed chemical constituents.

Since few significant differences in concentration were observed in the water flowing over the solid waste mixture, full-scale sampling of the interstitial water was initiated on day 9. The resultant data (November 1971 to January 1972) are presented in Figure III-2. Each dissolved waste constituent has been arranged in order of decreasing concentration, from the top to the bottom of the figure.

Following an initial decline of 20 mg/l between day 1 and day 4, the dissolved organic carbon concentration increased by approximately 16-fold between day 4 and day 9. Its concentration continued

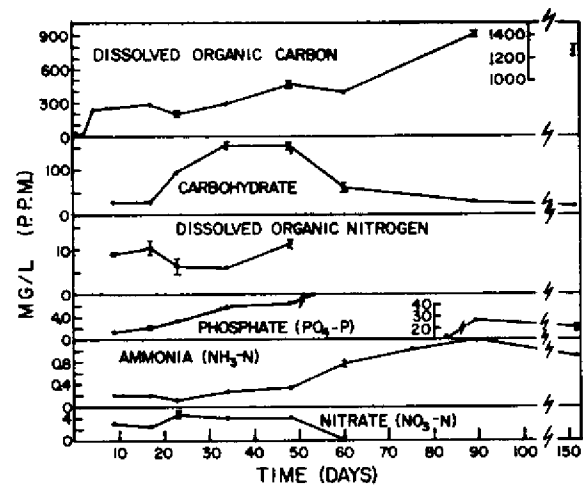


Figure III-2. Concentrations of dissolved substances in interstitial water of solid waste deposit in a flow-through tank (tank 1).

Table III-1. Concentrations of dissolved materials in eluate soon after placement of solid waste.

Day	Sample Source	Carbohy- drate (mg/l)		Dissolved Organic Carbon (mg/l)		Dissolved Organic Nitrogen (mg/l)	
		\bar{X}	Range	\bar{X}	Range	\bar{X}	Range
1	Upstream	2.5	0.2	2.5	1.0	0.20	0.06
	Downstream	8.4	1.4	10.0	2.0	0.42	0.01
4	Upstream	0.8	0.3	1.0	0.0	0.16	0.01
	Downstream	1.6	0.2	2.0	0.0	0.16	0.02

Table III-2. Oxygen concentrations in eluate.

Day	Oxygen (mg/l)		Temperature (°C)
	Upstream	Downstream	
1	7.8	7.6	14.8
4	7.6	7.2	14.3
5	7.9	7.6	11.1
8	8.4	8.3	9.2
9	8.6	8.5	8.8
12	8.2	8.2	9.8
17	8.3	8.2	11.0
23	8.9	8.9	5.0
34	9.3	9.3	7.0
48	9.2	9.2	6.5

to increase and had reached a value of over 1200 mg/l after 150 days. Carbohydrates began to accumulate rapidly about two weeks after the increase of dissolved organic carbon. The concentration in-

creased from 28 mg/l (day 17) to 154 mg/l (day 34) and afterward decreased to low values.

Phosphate and ammonia accumulated in the interstitial water, and appeared to level off or decrease after 90 days. Additional samples taken in June 1972 (day 212 and 239) (Figure III-3) show an extremely rapid rise in ammonia production rate at higher temperatures (over 15°C). The concentration of dissolved organic nitrogen was relatively constant with time. The nitrate concentration slowly decreased to near zero at 60 days.

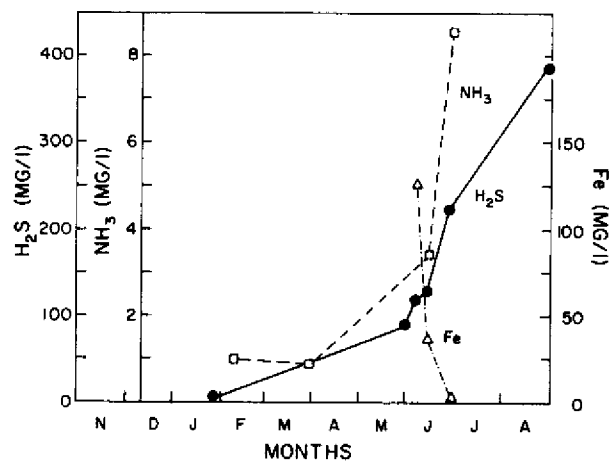


Figure III-3. Concentration of hydrogen sulfide, ammonia and dissolved iron in interstitial water of tank 1 (sample part 1, duplicate analysis).

The pH of a seawater extract of shredded paper was 5.6 after two weeks. The pH of the interstitial water was 5.4 after 77 days.

Oxygen determinations made with an oxygen electrode gave values of about 1.3 mg/l after day 17. Oxygen could have been depleted at this time since H₂S interferes with the operation of the meter.

A black precipitate of iron sulfide was observed near the deposit surface at 40 days. By 60 days the immediate subsurface material and pieces of yellow plastic had turned grey. Hydrogen sulfide levels were determined by iodine titration (Gaines and Pilson, 1972) at intervals from January 26 (day 77) to September, 1972. These are shown in Figure III-3 with some values for ammonia and dissolved iron. H₂S concentration increased at an accelerated rate during June. At this time interstitial samples taken from 3 cm below the deposit surfaces contained 200-400 mg/l H₂S and near zero iron.

The sulfide in the eluate from tank 1 was measured on a number of occasions. Variations in flow rate make it difficult to interpret these values in terms of production rates; however, a gradually rising trend was found during weekly determinations in June (0.14, 0.34, 0.46, 0.69 mg/l).

Upstream-downstream analyses of O₂, H₂S, and NH₃ were made on July 7 and 10, 1971, at a reduced flow rate (0.67 cm/sec) and at a temperature of 19-20°C. Decrease in oxygen was 0.46 and 0.58 mg/l, ammonia was at background levels, and hydrogen sulfide increased by 0.69 and 0.70 mg/l (Table III-3).

Table III-3. Concentrations of ammonia, oxygen, and hydrogen sulfide in flowing and recirculated eluate in mg/l (test 1 July 7, 19°C; test 2 July 10, 20°C).

	NH ₃		O ₂		H ₂ S	
	1	2	1	2	1	2
<i>Flow-through</i> (8.8 l/min)						
upstream	.013	.011	7.41	7.10	0.0	0.0
	.018	.016	7.35	7.17	—	—
downstream	.027	.018	6.83	6.57	.68	0.70
	.023	.027	7.02	6.55	.70	0.71
control	.023	.019	7.71	7.11	0.0	0.0
	.027	.015	7.67	7.20	—	—
<i>Recirculated</i> (18 l/min)						
0.5 hour tank 1	.055	.041	6.25	6.09	.51	0.79
	.046	.047	6.36	6.17	.59	0.76
control	.027	.026	—	—	<.01	<.01
	.036	.022	—	—	—	—
1.0 hour tank 1	—	—	4.66	4.43	—	—
	—	—	4.50	4.75	—	0.82
control	—	—	7.26	7.06	—	<.01
	—	—	7.43	6.98	—	—
1.9 hour tank 1	.055	.059	—	—	.43	.77
	.064	.049	—	—	.43	.76
control	.041	.028	—	—	.016	—
	.036	.025	—	—	.011	—
2.7 hour tank 1	.036	.060	3.68	3.31	.97	.78
	.036	.065	3.65	3.42	.86	.85
control	.018	.031	6.89	6.80	0.0	<.01
	.027	.033	7.10	6.70	—	—

On the above dates water was circulated over the waste deposit and O₂, H₂S, and NH₃ monitored.

The surface of the water was open to the air. Values are shown in Table III-3. In each case oxygen declined steadily at a rate of 1.3 mg/l/hr while H₂S and NH₃ increased slightly.

Closed System—Description

Dissolved materials in the interstitial water of submerged waste were monitored in closed systems. These consisted of four glass tanks 12" x 24" x 18" containing a block of waste with a dry weight of 20 lbs/cubic foot (0.27 g/cm³). The tanks were held in a water bath at 9 ± 0.5°C. Analyses were made over an 80-day period.

Four combinations of conditions were studied. These included: (1) 9.8% "food" in waste in salt water (tank 1), (2) 2.2% "food" in waste in salt water (tank 2), (3) 9.8% "food" in fresh water (tank 3), and (4) 9.8% "food" in salt water poisoned with 100 ppm mercury chloride.

Samples were taken through a filter stone buried approximately 20 cm in the waste. Water level was kept slightly above the surface of the waste and was replaced at the surface to make up that lost to sampling. During the course of the experiment about one-fourth of the volume of the tank was replaced.

Closed System—Results

The results of analyses are shown in Figures III-4 through III-12. In most cases the difference in levels between parts in a single tank was within the precision of the analytic technique. There were, however, large variations in levels from the two ports in tank 1.

Dissolved oxygen (Figure III-4) was reduced to zero by 6-8 days in the unpoisoned tanks and by 17 days in the poisoned tank. Hydrogen sulfide (Figure III-4) increased markedly in unpoisoned salt water tanks after day 54.

The pH (Figure III-5) fell from seawater levels (slightly over 8) to about 6 as soon as water was added to the waste. The pH remained at this level in the poisoned tank but dropped to 4.8-5.2 in the others. After 30 days there was a trend towards increased values in saltwater tanks.

Nitrate (Figure III-6) and nitrite, which was detected by the nitrate analysis, fell to zero in the unpoisoned tank at the same time that oxygen was

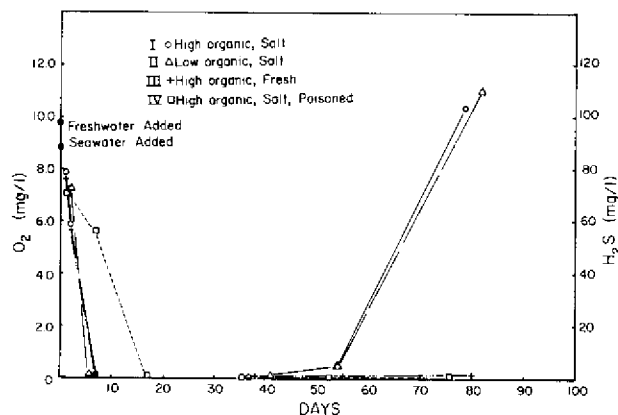


Figure III-4. Concentration of oxygen and hydrogen sulfide in interstitial water of solid waste in closed tanks at 9°C.

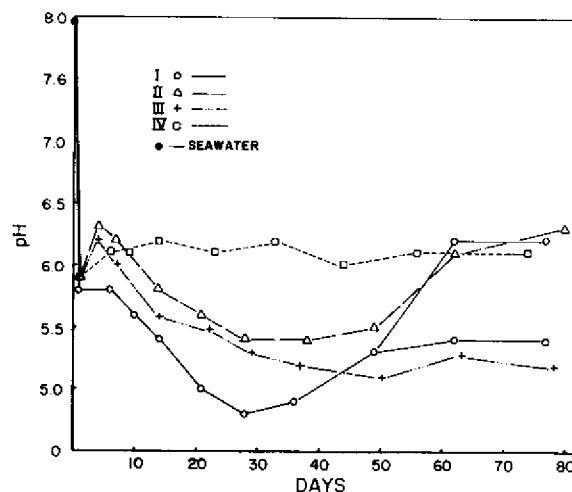


Figure III-5. pH of interstitial water of solid waste in closed tanks at 9°C.

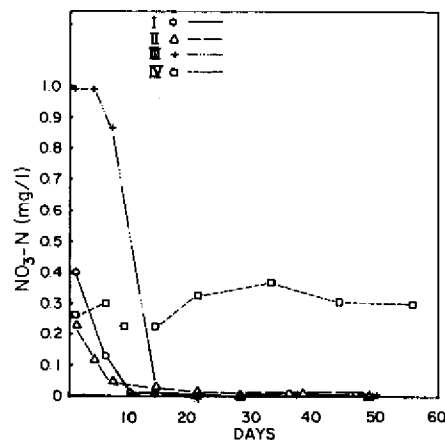


Figure III-6. Concentration of nitrate in interstitial water of solid waste in closed tanks at 9°C.

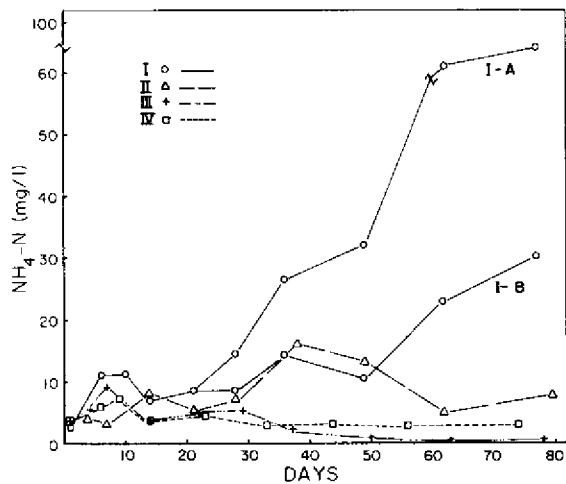


Figure III-7. Concentration of ammonia in interstitial water of solid waste in closed tanks at 9°C.

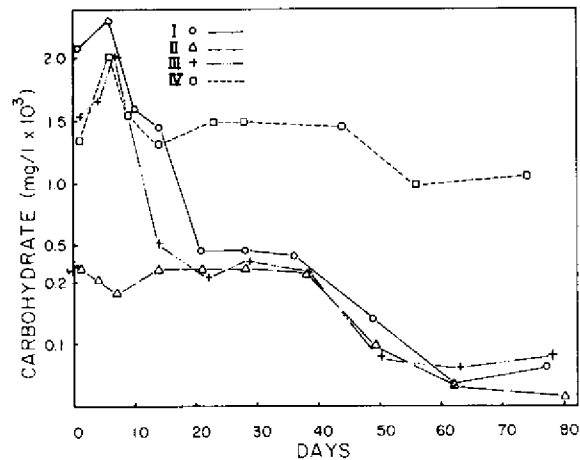


Figure III-9. Concentration of carbohydrate in interstitial water of solid waste in closed tanks at 9°C.

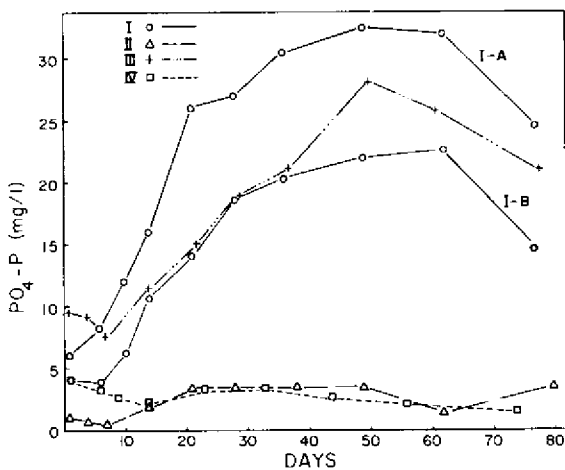


Figure III-8. Concentration of phosphate in interstitial water of solid waste in closed tanks at 9°C.

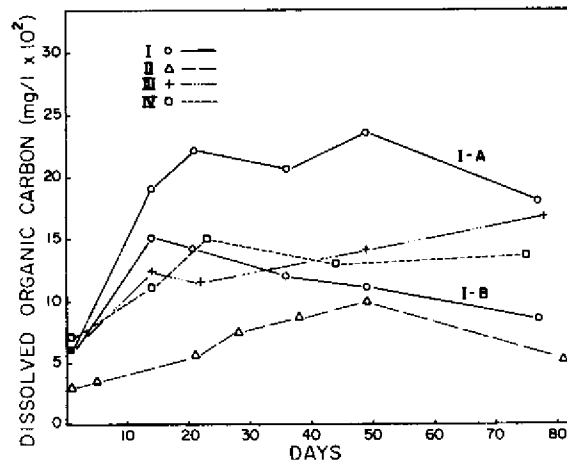


Figure III-10. Concentration of dissolved organic carbon in interstitial water of solid waste in closed tanks at 9°C.

consumed. Nitrate remained at 0.2-0.3 mg/l in the poisoned tank. Ammonia (Figure III-7) was very low in the freshwater tank and reached highest concentrations in the high-food saltwater tank.

Phosphate (Figure III-8) remained below 5 mg/l in the poisoned and low "food" tank. In the unpoisoned high-food tanks, it rose to 22-32 mg/l after about 50 days and either leveled off or decreased near the end of the experiment.

Carbohydrates (Figure III-9) remained at about 1500 mg/l in the poisoned tank but steadily decreased to less than 100 mg/l by 80 days in the other tanks. Dissolved organic carbon (Figure III-10) did not vary as much as many of the other

constituents. It increased and then leveled off in most of the tanks. The high-food tanks, both poisoned and unpoisoned, had higher levels than the low-food tank.

Turbidity (Figure III-11) remained low in the poisoned tank. In the high-food saltwater tanks turbidity increased rapidly and then leveled off. The increase was slower in the low-food tank. Precipitation of sulfur interfered with readings from part I-B.

Dissolved iron (Figure III-12) remained at about 10 mg/l in the control, increased and then fell in the saltwater tanks (except I-B), and increased steadily in freshwater.

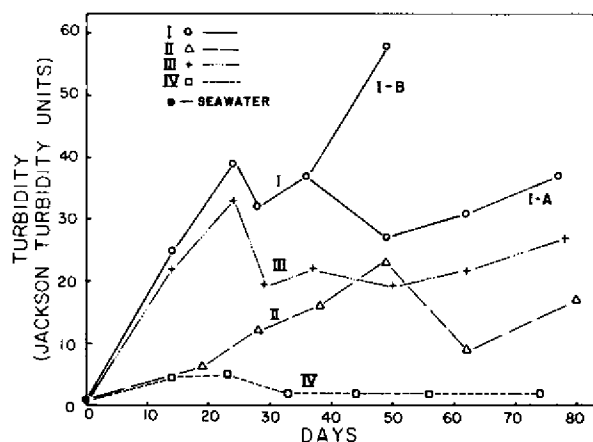


Figure III-11. Turbidity of interstitial water of solid waste in closed tanks at 9°C.

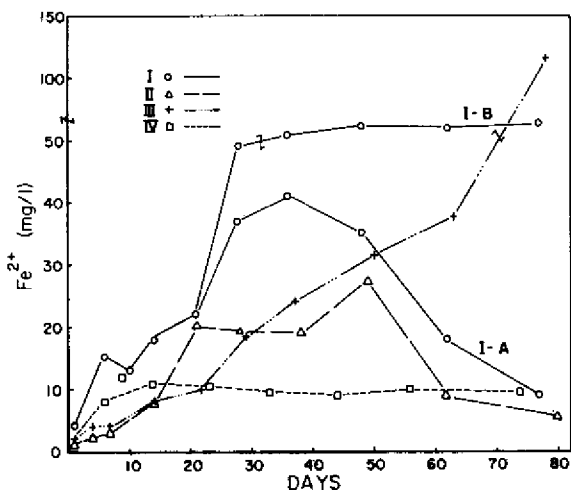


Figure III-12. Concentration of dissolved iron in interstitial water of solid waste in closed tanks at 9°C.

The levels of ammonia, dissolved organic carbon, carbohydrate, phosphate, and turbidity were all lower in the low-food than the high-food tanks.

The contents of the closed tanks were examined after they had been held 80 days at 9°C and 90 days at room temperature. The saltwater tanks had a strong odor of H₂S. These tanks contained additional very strong smelling degradation products. Food substances appeared as patches of pasty material. All paper products seemed to be intact, printing was legible and fibers were clean. The sections of tin cans were only blackened around cut edges. Tin and plastic coated surfaces were unaffected. Aluminum foil seemed slightly pitted.

Discussion and Projections

Jannasch (1970) has conducted degradation experiments at depths of 4300 and 5300 meters lasting 2 to 5 months. He reported that degradation rates were 10-100 times slower than at the surface at the same temperature. He ascribed this effect to an increase in maximal temperatures required for growth and enzymatic activities with increased pressure. It appears that the normal bacteria of the deep sea are very slow-growing and are adapted to very low substrate concentrations. The possibility of the development of a more active microbial population on an organic deposit in the deep sea is the subject of active research by Dr. Jannasch and his associates.

Oxygen was consumed in the interstitial water in a few weeks time in all experiments with unpoisoned waste. Even in the poisoned tank, chemical demand consumed all oxygen in less than 20 days. Although oxygen consumption rates will be low at deep-sea disposal sites it can be safely assumed that the internal portions of waste bales will eventually become anoxic. Laboratory results dealing with anaerobic systems will thus be applicable to all dumping areas. Studies of pressure effects on anaerobic bacteria would be an important contribution in understanding massive deep-sea organic deposits.

Marine microbiologists (H. Jannasch, pers. comm. and J. McN. Sieburth, 1973) have stated that motile scavengers are more important than bacteria in the initial degradation of large particles of organic matter in the deep sea. Bacteria will be relatively more important in the case of massive waste bales with anoxic internal environments.

Nitrate was rapidly consumed in unpoisoned waste. Denitrification has been described by Redfield, Ketchum and Richards (1963), and many other authors. Nitrate serves as an alternate hydrogen acceptor after oxygen is consumed. Nitrogen gas, carbon dioxide and water are produced. Nitrogen compounds which are plant nutrients or behavior-stimulating substances become biologically inactive as nitrogen gas.

When oxygen and nitrate have been consumed sulfate is used as a hydrogen acceptor by sulfate-reducing bacteria (*Desulphovibrio*). Organic matter is degraded to carbon dioxide, water, and hydrogen sulfide. Hydrogen sulfide concentrations which

were measurable after 40 days in the closed tanks rose rapidly between 50 and 80 days.

Concentrations were continuing to rise in the closed tanks at the end of the sampling period. Sulfide determinations made in the flow-through tank reached 386 mg/l in 10 months and had decreased to 270 mg/l after 18 months. The highest values measured represent reduction of approximately half the sulfate in seawater. Although marine isolates of *Desulphovibrio desulfuricans* will tolerate H₂S up to 1000-2500 mg/l (Miller, 1950), it is not known whether high concentrations of H₂S will limit activity rates in waste deposits.

The low values of sulfide in the freshwater tank indicate the minor importance of sulfide originating from sulfur-containing amino acids in food.

Sulfide precipitated dissolved iron in both open and closed systems. Figure III-3 illustrates this effect in tank 1. During a 31-day period 125 mg/l of dissolved iron was precipitated. This reaction would consume 76 mg/l of H₂S. During that period 131 mg/l of H₂S accumulated and some diffused out of the system. At the organic matter levels present in these experiments, sulfide production is able to "overwhelm" iron released by corrosion. After readily degradable organic matter has been consumed, sulfide production will slow and it is conceivable that iron could react with and reduce the concentration of sulfide in interstitial water (see section on diffusion of metals).

Zajic (1969) states that almost any form of organic matter (including cellulose and lignin) will support growth of sulfate reducers. It will be important to determine whether the rate of degradation at reduced temperature and high pressure is more than negligible in order to predict the longevity of bales.

The internal environment of submerged waste bales will be acid. Paper products produce an initial acid reaction. Production of CO₂ by oxidation, denitrification, and sulfate reduction and production of organic acids from fermentation lowers the pH more. The pH remains low in fresh water but increases in salt water due to buffering by the sulfide system (Gaines and Pilson, 1972). Loss and consumption of CO₂ and ammonia production may also contribute to an increase in pH.

In these experiments ammonia levels increased more rapidly and reached higher levels in the closed

tanks than in the flow-through tank. Since this can only be partially ascribed to temperature and since levels were still increasing at the end of the experiment it is difficult to choose a level of ammonia on which to base projections. The highest levels reached fall in the range of levels in organic-matter-rich natural sediments at a depth of about one meter (Table III-4). These levels are much higher than in open ocean sediments.

If it is assumed that interstitial ammonia remains in unfixed form, the flux of ammonia from a solid waste deposit would be the same as an equal area of sea floor in an oxygen-deficient basin, but 10 to 100 times higher than from normal deep-sea sediments. Thus a km² dump would generate as much ammonia as 10 to 100 km² of normal sea floor. This is inconsequential in the open ocean (the Atlantic is 82 million km²), but could be important in in-shore waters where nitrogen is the limiting nutrient (many New England estuaries: Ryther and Dunstan, 1971).

In the closed tanks, ammonia concentrations as high as 60 mg/l were measured. The level of acute toxicity for fish is 1-5 mg/l, but the toxicity of ammonia for infaunal invertebrates is not known. Future lines of inquiry should include effects on in-fauna as well as on the behavior of motile animals. Such studies would be applicable to a variety of marine problems.

Dissolved phosphate reached very high levels in waste relative to natural sediments (Table III-4). The rapid release of phosphate from degrading organic matter is well known and may partially explain the unusually high ratio of phosphate to ammonia.

Many of the mechanisms which contribute to the fixation of phosphate in natural sediments may be absent as reduced in anaerobic solid waste. Phosphate is strongly adsorbed by natural sediments (Jitts, 1958 reported 80-90% adsorption in suspensions containing 0.55 to 2.55 mg of PO₄-P and 2.99 g silt in 1.25 l). Although solid waste has a considerable surface area of cellulose fibers (roughly 0.5 m²/g), this is small compared to the area of fine-grained sediments (Weiler and Mills (1965) give measured values of 2-20 m²/g and 10-45 m²/g for shelf and slope sediments). Phosphate is fixed in sediments as ferric phosphate. A recent study by Patrick *et al.* (1973) clearly demonstrates the

Table III-4. Ammonia and phosphate concentrations in interstitial water of marine sediments and experimental solid waste deposits.

Location	Depth below surface (cm)	NH ₄ -N (mg/l)	PO ₄ (mg/l)	Reference
Oxygen deficient basins off southern California	0-50	2.5-40.6	0.10-1.73	Rittenberg <i>et al.</i> , 1955
	50-100	4.8-68.6	0.12-2.65	
	100-150	16.8-85.5	0.2 -1.42	
	150-200	26.6-159.8	0.03-6.02	
Deep sea floor, northwest Pacific	0	1.2	0.08	Brujewicz and Zaitseva, 1959
	100	0.67	0.09	
	200	1.2	—	
	300	—	0.18	
	400	3.4	0.10	
Bering Sea * from bay of high biological production	0	0.24-45.0	0.17-6.3	Zaitseva, 1954
	100	1.3 -111.0	0.17-4.5	
	200	3.0 -159.0*	0.25-4.7	
	400	5.0 -145.0	0.69-7.5	
	800	6.4 -21.5	0.35-4.4	
	1600	18.6 -31.8	3.0 -5.4	
Black Sea	0-10	0.17	0-10	Brujewicz and Zaitseva, 1959
Solid waste, flow-through tank	20		8.5 (10 months, level still increasing)	
	20		28 (max. at 90 days)	
	20		30,82 (80 days, still increasing)	
	20		22,28,33 (max. at 50-60 days)	

effect of low pH and Eh on the solution of this mineral. The presence of sulfide would also release phosphate since it combines much more strongly with iron than phosphate does (M. E. Q. Pilson, pers. comm.).

A maximal rate of release of phosphate from a waste deposit could be determined by considering all phosphate to be mobile and expected to diffuse from the waste at a rate consistent with concentration gradients and diffusion coefficients.

Information on the degradation process in compacted waste will become more available with increasing use of compression in landfill disposal. Carver (1970) presented data from Japanese research on compressed waste blocks. The maximum BOD and COD of water extracted from compressed blocks was an order of magnitude less and occurred 10-20 days later than in water from untreated waste. The mechanisms responsible for these decreased levels need to be clarified. It appears that low rates of degradation would necessitate longer times to stabilization but this did not occur in the case of compressed waste in fresh water reported by Carver (1970). In both compressed and un-

treated waste, submergence in salt water had the effect of doubling the level of COD and prolonging the period of high BOD and COD, a result consistent with the production of H₂S.

Diffusion Rates in Solid Waste

Dissolved materials diffusing from a solid waste deposit are rapidly diluted by flowing water to levels below limits of detection. In the laboratory water can be recirculated over a waste deposit until pollutant levels are measurable. An alternative method for estimating the flux of materials out of a waste deposit consists of measuring interstitial concentrations and applying diffusion coefficients appropriate for various matrix-pollutant combinations.

Diffusion rates through sediments are a function of concentration gradient, ionic size of the diffusing substance, temperature, and geometry of the solid-liquid system. Duursma (1966) suggested several mechanisms by which small pore size could retard molecular diffusion in sediments. However, in experiment with metals in sediments containing clays, adsorption reactions controlled the actual rate of

movement of the metals through the sediment, masking the effects of grain size. In Duursma's experiments, sediments with grain size larger than 0.5 mm had diffusion coefficients close to those in water (values in clean fine sand in units of 10^{-5} cm^2/sec at 20°C : Fe^{3+} 0.16, PO_4^{3-} 0.22, SO_4^{2-} 0.30, Cl^- 0.55, Na^+ 0.59).

Adsorption effects would be less important in waste deposits than in fine-grained sediments, although cellulose fibers can be activated to react with organic pollutants (Institute of Forest Products, 1971) and have measurable mercury adsorbing action (Suggs *et al.*). Movement of sulfide is clearly affected by reaction with oxidized or dissolved iron. In the absence of reactive iron, measured sulfide diffusion rates should be similar to those of chloride or sulfate.

While it seems intuitively that highly compressed solid waste would have lower diffusion coefficients than less dense waste, there is actually no way of predicting whether such a relationship exists, and if it does, what the change in coefficient would be. Little can be learned from the behavior of natural sediments because of the great differences in constituent particle size, shape, orientation, and elasticity.

Determination of diffusion coefficients is technically difficult and measurements in solid waste were not attempted. Permeability, the capacity of a porous medium to transmit a liquid, is easily determined by standard methods. The permeability of compressed waste would affect the flow of water through bales on submergence and during absorption, or generation of gases. There is probably also a gross relationship between permeability and diffusion rate.

The permeability of milled paper compressed to various densities was determined as a basis for future work on mechanical properties of waste. Tests were performed on a series of cylinders (5.25 cm diameter, 8.5 cm long) containing various densities of paper. The values obtained fall on a relatively straight line on a semilog plot (Figure III-13) consistent with results on soils (Lambe, 1951). Rate decreases during replicate runs were probably caused by air coming out of solution and forming obstructive bubbles. Swelling of fibers could also cause this effect. Rate of flow was extremely low at densities in the range that would be used in ocean

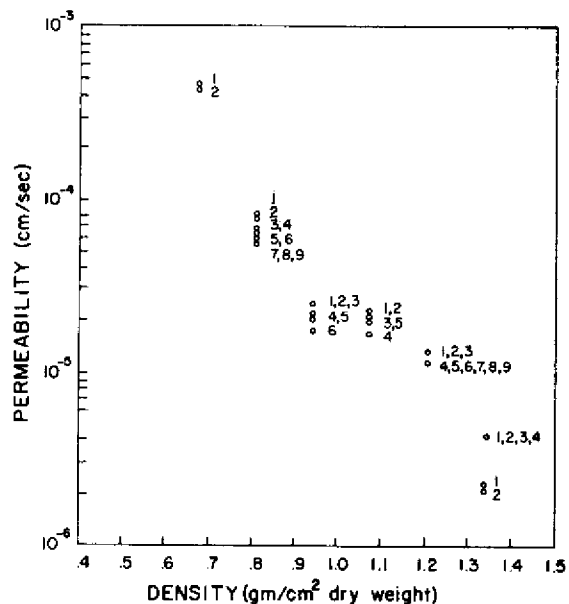


Figure III-13. Permeability of compressed milled paper at various densities (tap water, 20°C). Numbers refer to order of replicate runs on samples.

dumping. Actual bales would contain less finely milled and more heterogeneous material.

It appears that diffusion rates in water should be used for initial modeling of pollutant flux from a waste deposit. Further laboratory measurements will be necessary to establish actual flux as a function of reactions with solids and waste compaction.

Diffusion of Metals from a Submarine Waste Deposit

Important constituents of a submarine solid waste deposit would include cellulose in various forms, biochemically inactive glass and plastic, and a high content of iron and degradable organic matter relative to a natural sedimentary deposit. Many other metals would be present as a result of use in packaging, plating, housewares, and electrical equipment. The values on page 21 are rough estimates of the metal content of Boston solid waste derived from analyses of incinerator ash (First, 1972).

It is necessary to know the concentrations of metallic, dissolved, and chemically combined forms of various metals in solid waste in order to predict retardation of biological degradation of the waste by toxic metal ions, fixation of nutrient or polluting compounds as insoluble metal precipitates, and tox-

Metal	Weight (% ash particles less than 1/2")*
Iron	4.0
Zinc	0.5
Lead	0.4
Copper	0.1
Manganese	0.07
Nickel	0.007
Chromium	0.006
Cobalt	0.002
Cadmium	0.001

* Weight reduction on incineration is 50-75%. Particles less than 1/2" made up about 50% of Boston incinerator residue; tin cans made up about 15% of total residue.

icity to colonizing infaunal animals. The solubility of the metals, permeability of the deposit, and concentration gradients of metals and reacting compounds are important determinates of diffusion out of the waste. Metals leaving the deposit could have toxic effects on epifaunal animals and contribute to levels of dissolved and suspended metals in the surrounding waters.

Most studies on the chemistry of metals in seawater deal with metals in aqueous solution or in oxidized forms (oxides, hydroxides, etc.). Corrosion is the process of solution and oxidation of the metallic forms. Corrosion rate is a function of the electrode potential of the metal in solution; the chemical and physical homogeneity of the metal and surrounding matrix, the formation of a protective coating on the metal; and the pH, oxygen concentration, ion concentration, flow rate, diffusion rate, and temperature of the solution (Horne, 1969).

Attempts to predict the concentrations of metals in seawater from equilibrium models based on the solubility of the least soluble compound which can be formed with the major ions, have resulted in values much lower than are actually found. Biological processes, complex ion exchange and solid solution reactions with solid phases may be more important in determining the behavior of many metals in seawater (Gross, 1970).

Equilibrium models may be no more predictive for metal concentrations in anaerobic interstitial water. Although concentrations of reactants are high and biological processes are somewhat simplified, sorption reactions and the formation of polysulfide complexes are major problems in this environment.

For many metals in oxygenated bottom deposits

the formation of insoluble compounds and sorption results in a low flux from the sediments to the overlying water. If the sediment has a high content of organic matter, the chemical environment will change in ways which may have opposing effects on the mobility of many metals.

On the one hand degradation of organic matter causes lowered oxidation reduction potentials, increased acidity, and lowered oxygen levels which increases the solubility of many metals. The mobilization of insoluble ferric hydroxide by conversion to soluble ferrous ions in anoxic sediments of lakes is well known.

The opposite effect results when hydrogen sulfide is produced by anaerobic bacteria in marine sediments. Sulfide quantitatively precipitates several metals. It reacts with iron minerals (ferric oxyhydroxides—Berner, 1969) to form iron sulfide and free sulfur. A black insoluble precipitate forms in the deposit. R. A. Berner has constructed a number of laboratory sediment models in which he varied iron-sulfate ratios and the position of layers with high organic matter content. In "high iron" experiments (iron/sulfate ratio greater than 10) sulfide reacted with iron within the organic source zone and did not diffuse out of it. There was a concentration of iron within the zone. When the iron-sulfate ratio was lower, sulfide diffused out of the organic layer and fixed iron throughout the sediment.

In the case of solid waste with low available iron, "excess" sulfide would diffuse from the sediment surface. In order to fit the "high iron" criteria of Brenner, a deposit with 70% porosity would need to contain 200 moles/l of reactive iron. Although typical solid waste contains a high percentage of metallic iron, corrosion is necessary to provide reactive iron. Although cases of rapid corrosion of steel in sulfide rich muds have been reported (0.62 mg/cm²/day—Cameron and Robinson, 1968), corrosion of tin plate within solid waste deposits was negligible.

It appears that there will be little effect of iron "fixing" or "detoxifying" hydrogen sulfide in these deposits. Sulfide production will continue in a solid waste deposit as long as degradable substrates remain. Solid waste consists of a small percent of easily degradable organic matter and a very large quantity of cellulose which seems to be more resistant.

Table III-5. Mobilization of selected metals in anoxic marine sediments.

Metal	Released to Water	Remarks	Source
Cadmium	unknown	Possibly released at the mud-water, interface aided by biogenic activity.	Brooks <i>et al.</i> (1968)
Cobalt	yes	Goes into solution when reduced. Its sulfide is soluble and concentrations of the metal in anoxic waters have been found to be greater than that in oxygenated waters.	Piper (1971); Bonatti <i>et al.</i> (1971); Brooks <i>et al.</i> (1968); Krauskopf (1956)
Copper	no	Immobilized as sulfides, not detected in H ₂ S-bearing waters.	Piper (1971); Bonatti <i>et al.</i> (1971); Richards (1965 a, b)
	yes	Large amounts of Cu ions exist in the exchangeable form in organic-rich sediments. Not removed from water altogether by the presence of sulfide. Dissolved sulfide may cause the formation of soluble metal polysulfides.	Toth and Ott (1970); Brooks <i>et al.</i> (1971); Krauskopf (1956); Barnes and Czamanske (1967)
Chromium	no	Relatively insoluble in reduced state.	Bonatti <i>et al.</i> (1971)
	yes	Tends to go into solution at pH around 6.9—concentrations have been found to be slightly higher in anoxic waters.	Piper (1971)
Iron	yes	Increase in solubility directly related to decrease in redox potential and pH in anoxic environments. FeS more soluble than Fe(OH) ₃ , concentration in sulfide-bearing waters 5 times that in oxygenated waters have been reported.	Piper (1971); Toth and Ott (1970); Richards, <i>et al.</i> (1965); Richards (1965 a, b); Berner (1969); Nacci, <i>et al.</i> (1970); Brooks <i>et al.</i> (1968); Borchert (1965)
Iron	no	In sediments where Eh is low enough for Fe reduction, but not low enough for sulfate reduction, some Fe might be mobilized. Usually immobilized as insoluble sulfides.	Bonatti <i>et al.</i> (1971)

The chemistry of iron is important because of its high concentration in sediments and waste, interaction with toxic hydrogen sulfide, and ability to sequester phosphate (an important plant nutrient). Other metals are important mainly because of their toxic properties. Table III-5 summarizes the conclusions of recent studies on the mobility of various metals in anoxic sediments.

The closely related toxic metals (copper, zinc and cadmium) should be immobilized as insoluble sulfides in anoxic marine water but are found in relatively high concentrations. Brooks, Presley and Kaplan (1968) ascribe this to the formation of soluble metal polysulfides. They unfortunately do not discuss this reaction in detail.

Cobalt, manganese, and nickel all are more readily soluble in anoxic water than they are in oxic water. They would be expected to appear in high concentrations in the interstitial waters of a waste

deposit and to diffuse out into anoxic bottom water.

Jernelov (1969) and Fagerstrom and Jernelov (1972) discuss the complex transformations of mercury in aquatic ecosystems. Volatile, highly toxic methylmercury is produced when microorganisms methylate divalent mercury. Since mercury sulfide is insoluble it would appear that methylation would be prevented in anaerobic conditions. When Jernelov (1969) added mercury sulfide to anoxic sediments, no methylation took place; however, he found that mercury bound to organic matter could be methylated even in the presence of hydrogen sulfide. A threshold value of 1-10/ppm of mercury may exist for methylation to take place in lake sediments (Jernelov, 1969).

Other reports on the control of mercury in aquatic environments suggest that mercury flux from a waste deposit may be low due to adsorption. Suggs *et al.*, 1972 and Tratnyek, 1972 measured mercury

Table III-5. (cont'd.).

Metal	Released to Water	Remarks	Source
Lanthanum	yes	Goes into solution in reducing environments.	Bonatti <i>et al.</i> (1971)
Manganese	yes	Soluble, and highly mobile in anoxic environments. Can be mobilized in bicarbonate solutions under only slightly reducing conditions.	Piper (1971); Toth and Ott (1970); Bonatti <i>et al.</i> (1971); Nacci <i>et al.</i> (1970); Borchert (1965)
Mercury	no	Insoluble as a sulfide.	Jernelov (1969)
	yes	Organic matter bound form can be methylated by bacteria even in presence of H ₂ S.	Jernelov (1969)
Molybdenum	no	Enriched in sediments from anoxic regions due to precipitation of MoS ₂ .	Richards (1965-b)
Nickel	yes	Solubilized by the lowered Eh and pH in reducing sediments. Sulfide of Ni is soluble and causes it to go into solution rather than to precipitate.	Bonatti <i>et al.</i> (1971); Toth and Ott (1970); Brooks <i>et al.</i> (1971); Krauskopf (1956)
Thorium	no	No evidence of mobility.	Bonatti <i>et al.</i> (1971)
Uranium	no	Insoluble in reduced valence states. Maximum concentrations found in sediments underlying reducing waters due to precipitation.	Piper (1971); Bonatti <i>et al.</i> (1971); Richards (1965-b)
Vanadium	no	Insoluble in reduced valence state. Probably fixed in sediment as insoluble hydroxide or sulfide.	Bonatti <i>et al.</i> (1971)
Zinc	yes	In organic-rich sediments, large amounts of Zn existed in exchangeable form.	Toth and Ott (1970)
	no	Precipitates as sulfides. Enriched in surface sediments over reducing waters.	Piper (1971); Brooks <i>et al.</i> (1968); Krauskopf (1965)
Silver	no	Bound as sulfides.	Piper (1971)

adsorbing action in cotton meshworks and paper cellulose and in waste wool fibers. Feick *et al.* (1972) report a very high mercury binding capacity for a fresh water peat; a substance which may be similar to solid waste in cellulose content. It is unfortunate that it is not possible to estimate the surface areas of adsorptive materials in these experiments since metal concentration in river sediments has been shown to be directly related to measured surface area (Oliver, 1973).

It is clear that a series of empirical experiments are needed to indicate which effects will be dominant for toxic metals in organic marine deposits, those that increase or those that decrease mobility. It is possible that a solid waste deposit could be formulated in a way designed to limit the mobility of toxic metals.

IV. Gas Production in Solid Waste

In early stages of our experimental work with solid wastes, gas ebullition appeared as a common feature of seawater-wetted material. The production of gases within solid wastes could have a variety of physical, chemical and biological consequences and could also serve as a useful indicator of the progress of microbial degradation activities.

The series of analyses were performed in order to assess the role of gas and gas bubble formation with regard to the following contingencies: (1) lowered density of baled material with subsequent refloating or movement by bottom currents, (2) ejection of interstitial water which could inhibit internal decomposition activities or eject toxic pore-water solutions, and, (3) toxic effects of free and dissolved gases. It is clear that in (1) and (2) the important question is whether gas bubbles can be expected to form. The answer to this question depends upon the nature and rate of the gas production, the depth of the dumping site, and the nature of the baling process; a firm answer cannot be reached without these specifics. Direct toxicity depends upon the gases produced, regardless of whether they form bubbles. This study, performed on gases from experimental solid waste beds and slurries, may represent the first systematic analysis of gases produced in wastes in a seawater environment.

Gas Production in Natural Media

This report is concerned with all substances which are gaseous within environmentally reasonable ranges of aqueous conditions or which include a gaseous species in their equilibria within those ranges. An examination of the literature reveals that at least seven gases should be considered; these are: hydrogen (H_2), oxygen (O_2), nitrogen (N_2), methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2) and hydrogen sulfide (H_2S).

Ammonia (NH_3) is a gas but it would always occur as the dissolved species NH_4^+ (ammonium) in the pH range found in these experiments regardless of concentrations and is, therefore, not considered here.

Table IV-1 gives the composition of gases in, extracted from or generated by various media. H_2S reported in the table is actually "total sulfide" as given by the sum of sulfide species in the equilib-

rium: $H_2S (ag.) = H^+ + HS^- = 2H^+ + S^{2-}$. At pH = 7, about half of the total sulfide would be in the form of dissolved H_2S . CO_2 occurring in bubbles is reported accurately but CO_2 in the dissolved form is actually "total CO_2 " in the equilibrium $H_2CO_3 = H^+ + HCO_3^- = 2H^+ + CO_3^{2-}$. At pH = 7, about one-third of the "total CO_2 " is actually in the form of dissolved CO_2 . The other gases do not participate in hydrolysis reactions and their concentration when dissolved can be interpreted directly.

Table IV-1 shows that each of the gases considered constitutes a minimum of 5% of samples from at least one medium. CO is an exception, but it is known to be a product of certain biological activities and was reported in solid waste gases. CO might have been overlooked in other analyses because it has the same mass number as N_2 and would not be distinguishable in common mass spectrometer methods; in some otherwise convenient gas chromatography methods CO is inseparable from CH_4 (see below) and similarly would not be reported.

Methods

Experimental Apparatus

An experimental solid waste was prepared according to specifications given in Table IV-2. Basically, three kinds of experimental setups were employed: (1) a flow-through tank (10' x 1' x 1'; described in chapter II) containing a bed of solid waste under unfiltered seawater; (2) one-liter jars containing seawater slurries of individual components of the experimental solid waste; and (3) two-liter jars containing solid waste seawater slurries, with gas traps to allow volume change determinations (Fig. IV-1). Samples were collected from waste beds by probing the bed, catching freed gas bubbles by water displacement under an inverted funnel and drawing the sample into plastic syringes. For jars, the syringe extractions could be made directly through rubber sampling septa. In (2), where the experimental apparatus resembled the gas generators in Fig. IV-1, negative pressures resulting from gas consumption were compensated for by periodically adjusting the pressure to about 1 psi with helium gas. Minor air leakage inward was possible in these jars.

Table IV-1. Partial composition of interstitial or dissolved interstitial gas in solid waste and anoxic media.

	% Volume							Remarks	Source
	H ₂	O ₂	N ₂	CH ₄	CO	CO ₂	H ₂ S		
Lake sediments	0.2	0.5	28.8	64.5	0.0	2.0	P	Bubbles; shallow water.	Conger (1943)
	2		12	75		16		Produced from natural sediment in lab fermenter.	Allgeier <i>et al.</i> (1932)
	5.4	0.0	5.2	38.2		51		Dissolved.	Koyama (1964)
Marine sediments			49	49		2		Bubbles from sediment.	Bean (1969)
		0.3		1.7		98	P	Bubbles; shallow bay.	Olson & Wilder (1961)
Salt marsh peat		0.0	4.6	88		7.2		Dissolved; sample from 3700 m.	Emery & Hogan (1958)
		0.0	50	0.68		49.2		Probably gaseous and dissolved.	Emery & Hogan (1958)
Anoxic seawater		0.0				71.0	29.0	Dissolved; brackish coastal pond.	Gaines & Pilson (1972)
		0.0		1.5		90.0	9.0	Dissolved; 190 m in Lake Nitinat (a fjord).	Atkinson & Richards (1967)
		0.0		0.52		98.6	0.81	Dissolved; 1400 m, Cariaco Trench.	Atkinson & Richards (1967)
		0.0		2.9		90.0	9.6	Dissolved; 1600 m, Black Sea.	Atkinson & Richards (1967)
Anoxic lakewater		0.0	50	0.92		49.0		28 m in stratified lake.	Koyama (1964)
Solid wastes	0.3	6.6	75.0	4.2	0.07	16.0		Interstitial gas in landfill.	Calif. State W.Q.B. (1967)
	0.0	5.0	45.0	25.0		25.0		Interstitial gas in experimental solid waste silo.	Fungaroll & Steiner (1971)
				35.0				Bubbles under plastic skin of submerged bale at 15 m in seawater; 1 analysis.	Zafrow (Pers. comm., 1972)

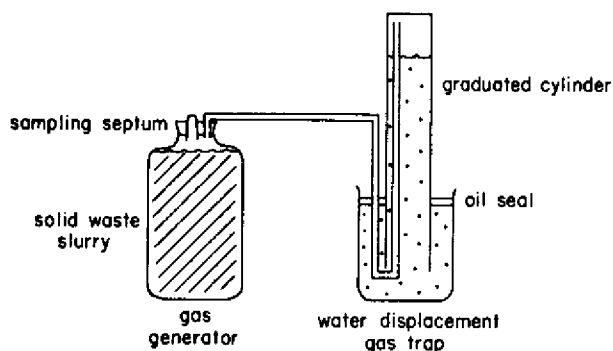


Figure IV-1. Gas generator and trap.

Gas Analyses

Analyses were performed within a few hours using a Perkin-Elmer Vapor Fractometer (Model 154). H₂, O₂, N₂ and CH₄ were determined using zeolite molecular (13X) at room temperature. With this column it was not possible to distinguish CH₄

Table IV-2. Composition of test solid waste.

Component	% Fresh Weight
<i>Paper and plastic (shredded)</i>	73.3
Sheet plastic	1.1
Newspaper	72.2
<i>Metal</i>	7.5
Shredded cans	6.7
Aluminum foil	0.77
<i>Glass</i>	9.6
Bottle fragments	9.6
<i>Food</i>	9.0
Purina Dog Chow	7.7
Rice	1.2
Sugar	0.13

from CO which is assumed to constitute a negligible or small fraction of values reported as "CH₄". CO₂ and H₂S were determined using a Porapak Q col-

umn at 50°C. Using this column, water vapor appeared as an irregular peak but could be distinguished from other peaks. The approximate analytical sensitivity determined, using pure gas standards and air, is indicated in Table IV-3. The normal precision of determination for each gas was better than 10%.

Table IV-3. Lower limit of detection of gas analyses.

Gas	ml/l	Volume %
H ₂	1	0.1
O ₂	0.2	0.02
N ₂	0.2	0.02
CH ₄	0.5	0.05
CO ₂	0.3	0.03
H ₂ S	1	0.1

Results

Flow-through Tank

Table IV-4 gives the results of analyses on gas samples from the large flow-through system for a period of more than half a year. The gases detected included O₂, N₂, CH₄, CO₂ and H₂S. On the average these made up 98% of the sample. H₂ was not detected. A reproducible but small peak occurring between N₂ and CO₂ on the Porapak Q column could not be accounted for; it was most prominent in later analyses.

The oxygen present could represent atmospheric contamination incurred during sampling; accordingly, nitrogen concentrations would also be affected.

Variations among "replicate" samples on a given date appear to be as great as variations between different sampling intervals. Apparently there was considerable heterogeneity in the microbial environments within the deposit. Analysis of dissolved substances (Chapter III) and visual inspections also indicated this. The concentrations of two gases, CH₄ and H₂S, showed a slight increasing trend with time ($r = 0.73$ and 0.58 respectively) which may actually have been a function of temperature. The concentration of CH₄ in gas samples increased at a rate of 1.6 ml/l/day. This datum cannot be used to calculate a production rate because the total gas content of the waste was not measured. H₂S could be detected in all samples. The total gas content of the waste was not measured. H₂S could be detected in all samples. The total sulfide concentrations in all cases would be higher than reported because only a portion would be in the gaseous form.

Gases Produced by Individual Solid Waste Components

The possibility was considered here that a few easily degraded components of the solid waste, notably the food items, could provide for essen-

Table IV-4. Composition of interstitial bubbles in seawater-saturated solid waste. (Tank 1) (ml/l and volume %).

Date	Age (days)	O ₂		N ₂		CH ₄		CO ₂		H ₂ S	
		(ml/l)	(%)	(ml/l)	(%)	(ml/l)	(%)	(ml/l)	(%)	(ml/l)	(%)
4/14	159	14	1.6	626	72.5	Tr	Tr	223	25.8	0.46	0.05
5/17	192	16	1.5	607	58.0	5	0.48	412	39.3	7.4	0.71
		14	1.4	393	38.9	21	2.1	535	52.9	48	4.7
5/24	199	25	2.7	707	75.2	27	2.9	162	17.2	19	2.0
		14	1.4	461	47.6	19	2.0	440	45.5	34	3.5
6/06	211	67	7.3	751	81.8	44	4.8	47	5.1	8.9	0.97
		11	1.1	207	21.0	55	5.6	618	62.6	96	9.7
		20	2.3	460	53.1	107	12.4	203	23.4	76	8.8
		23	2.1	778	71.0	96	8.8	154	14.1	45	4.1
Means		22.7	2.38	554	57.7	41.6	4.3	310	31.8	37.2	3.8
Sigma		17	1.9	188	19.7	38.1	4.1	196	19.3	32.6	3.5

tially all gas-producing activities, leaving the bulk of the waste as an inert matrix. Table IV-5 indicates the relative gas producing activities of jars containing seawater slurries of single and combined components. The jars identified as "PFM" (paper, food, metal) contained 20 gm/liter (800 ml per jar) of complete solid waste mixture; other jars were prepared by deleting various components. Slurries were used so that the medium could be maintained in a relatively homogeneous condition. The results presented here apply to the first month's activities. All jars containing food showed great gas exchange activity including initial O₂ consumption and CO₂ production, and, shortly afterward, significant production of H₂ (hydrogen) gas. Jars lacking food components showed less activity and did not produce H₂ in the interval studied.

Table IV-5. Gas exchange by model solid waste and its components. P = Paper, F = Food component, M = Metal component. Summary of a month's activity.

	Uptake O ₂	Production			
		H ₂	CH ₄	CO ₂	H ₂ S
PFM	+++	+		++	ppt
PF	+++	+		+++	+
PM	++			+	ppt
FM	+++	+	+	+++	ppt+
P	+			++	+
F	+++	+		+++	++

The "production" of CO₂ might be accounted for in part by a shift in the seawater carbonate system toward dissolved CO₂, resulting from the rapid initial decrease in pH common to these experiments (see chapter III). An interesting result is that while sulfide was eventually produced in all jars, it was measurable as the free gas only in those jars lacking the metal components. In jars containing metals a black precipitate typical of some sulfide minerals was formed but no H₂S could be detected analytically. An exception to this was jar "FM" in which a heavy black precipitate formed within days of initiation and in which free sulfide could be detected a few weeks afterward. Plain newspaper, with no added source of organic matter, produced H₂S.

The abundance of hydrogen gas in some jars was at first surprising since free hydrogen is not usually predominant in aquatic media and did not

appear in the flow-through tanks. However, hydrogen production is commonly encountered by microbiologists working with high organic media (Thimann, 1963) as a product, for example, of carbohydrate fermentation.

In the month's observations reported here, only the jars containing food and metal alone eventually produced CH₄.

In general the replicate treatments produced responses which were similar to each other but different from other treatments. An actual waste deposit probably includes a variety of microenvironments related to these various treatments.

Gas Production Sequence

In an attempt to quantitatively account for gas production, experiments were designed using two-liter gas generators with gas traps. The jars contained seawater slurries of the complete solid waste mixture and were incubated at two temperatures (8°C and 25°C) in darkness. Tests run on the gas trap showed that diffusive losses were relatively small compared with gas production rates normally encountered in 25°C trials.

The variability in response of replicate experiments is shown in Fig. IV-2. Gas production showed a lag phase lasting from 4-12 days, usually followed by a period of active production. Throughout the ensuing weeks periods of production were interrupted by periods of quiescence or net gas consumption. In instances of short quiescent periods, the accumulation of interstitial bubbles by agitation caused gas production to resume. In other instances, however, particularly during long periods of quiescence (or net consumption) agitation had no influence and gas production either did not resume or did so for unknown reasons. Gas production at 8°C occurred at a considerably lower rate.

In order to avoid accumulation of interstitial bubbles a loose slurry (19 g/liter) was employed in subsequent experiments. Figure IV-3 presents the observed gas volume record, plotted as a smooth curve to approximately daily observations. Figure IV-4 includes gas analysis data and is deduced from both volume and gas analysis results. The curves are probably not highly reproducible, but are suggestive of a likely sequence of gas production and consumption.

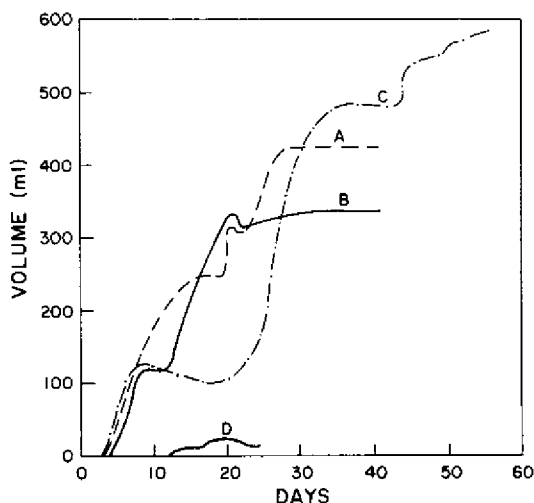


Figure IV-2. Gas volumes over slurries of solid waste in seawater. A and B contain 700g solid waste/l, C and D contain 38g solid waste/l (25°C).

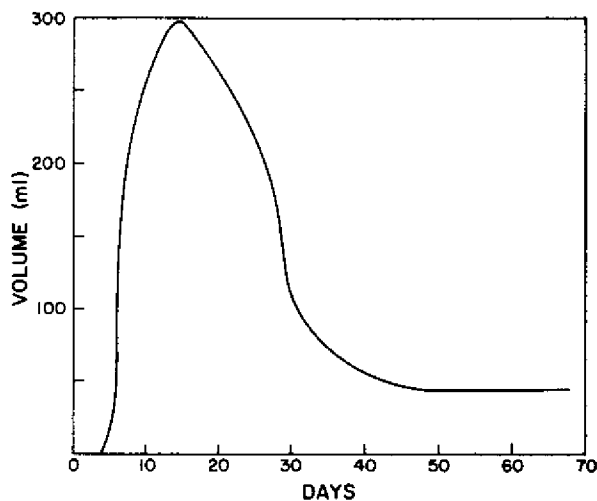


Figure IV-3. Gas volume over a loose slurry of solid waste in seawater (19g solid waste/l, 25°C) curve fits daily observations.

After the initial lag of four days, gas was produced for about 10 days followed by an almost equally rapid consumption which leveled off gradually to a quiescent condition of no net change. This vigorous activity, for the first 30 days, seemed to mainly involve changes in the amount of hydrogen gas. Major changes in N_2 levels can probably be explained purely as an associated dilution or concentration effect. Oxygen levels were low enough to have been caused by air contamination. Sulfide was first detected by smell on the 35th day and

appeared in all subsequent analyses. The decrease in H_2S after day 40 is not thought to be indicative of a long term trend in total sulfide. CH_4 was first detected on day 68.

Observations on Flotation of Solid Wastes

Flotation of solid wastes occurred in several experimental tanks. In one flow-through tank the solid waste bed "surfaced" 12 days after emplacement. This bed was covered and re-submerged using a plastic-covered wire screen with a 1" mesh. On day 83, the mesh was removed without consequence but on day 192 during spring warming the bed once again "surfaced."

In all experiments involving jars of solid waste slurries, the water-logged paper initially tended to sink, but the production of interstitial bubbles yielded a buoyant mass. In loose slurries bubble entrapment was less pronounced and could be prevented by periodic agitation.

Observations on weight changes were made on an experimental solid waste bale which was wrapped in perforated plastic using steel straps and submerged in a tank of seawater. The bale was packed with moist waste and had an initial negative buoyancy (density = 1.06 g/cm³). Water was soaked up for three days, but then was expelled by gas production until day 26 when the bale had a slight positive buoyancy. After gas was released from the plastic skin, the bale remained submerged for at least 20 days but eventually became buoyant once again.

Discussion and Projection

Gas Production

The sequence of gas consumption and production in homogenized media followed a pattern which is consistent with other work on degradation of organic matter. This sequence, given by Richards (1965), Koyama (1964) and others is as follows: (1) consumption of free O_2 and liberation of CO_2 , (2) reduction of nitrate and nitrite to N_2 , (3) reduction of sulfate (SO_4) to H_2S , and (4) production of CH_4 .

Rapid consumption of oxygen occurred in all experiments with whole or partial mixtures of solid waste, including plain newspaper. This rate, determined from the O_2 decrease in experimental jars

was $82 \text{ ml Kg}^{-1} \text{ day}^{-1} \pm 20\%$ at 25°C for newspaper (dry weight) and was considerably greater when the food component was added. Obviously, oxygen consumption ended when free O_2 was consumed. In all cases this occurred within a few days.

The microbial liberation of CO_2 was probably of the same general magnitude as that associated with pH dependent shifts in the seawater carbonate system which could produce up to about 45 ml L^{-1} . The cause of the rapid drop in pH (chapter III) is unknown, but is apparently related to paper chemistry.

Microbial production of N_2 by reduction of NO_3 and NO_2 may have occurred. The trend in N_2 concentration shown in Fig. IV-4 (days 40-70) would suggest this, but the background levels of N_2 from enclosed air was too high to firmly demonstrate the process. In addition, an adequate source of nitrate or nitrite is difficult to account for.

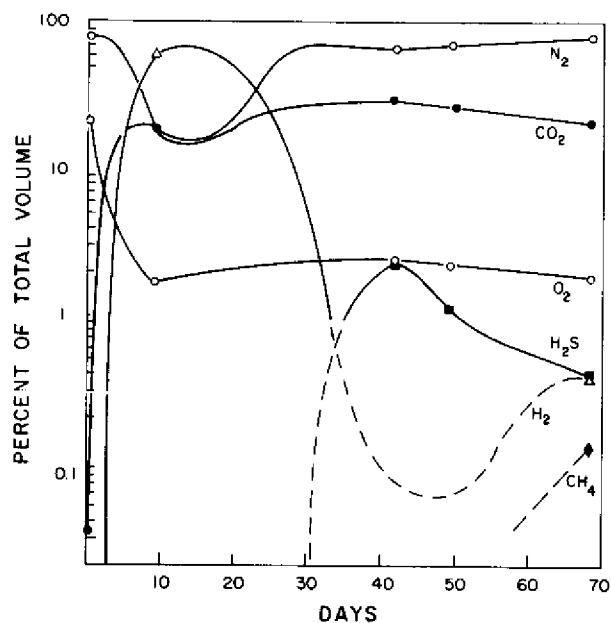


Figure IV-4. Composition of gas (% of total volume). Curves are drawn on the basis of 5 gas analyses and daily volume determinations.

H_2S production, which occurred in all experiments, commenced several days after oxygen had been consumed. As in natural sediments, the upper limit of H_2S produced is defined by the availability of sulfate, i.e. about 28 ml/l in seawater. Where metals are available to form sulfide precipitates, some or all of the H_2S will be removed as it is

formed. This was observed in experiments on solid wastes where metals were provided. However, the short term availability of metals depended upon their being added as oxides or in easily oxidized form. Fragments of cans which were coated with varnish or plastic had very little active surface area to react with H_2S .

As is pointed out by Richards (1965b), on a thermodynamic basis CH_4 would not be expected to form in an environment containing $\text{SO}_4^{=}$ if it results from CO_2 reduction. According to this argument, where sulfate seems available, CH_4 production could take place only in microenvironments that are impoverished in $\text{SO}_4^{=}$. It is known, however, that CO_2 reduction is only one pathway for CH_4 production (Koyama, 1964). Furthermore, the thermodynamic argument is useful only when both kinds of process are carried out by the same organism, which is contrary to the results of microbiological investigations (Thimann, 1963). Therefore, it was not surprising to us to find CH_4 production in SO_4 rich media. As illustrated in Fig. IV-4, however, the initiation of CH_4 production did lag behind H_2S production by more than a month. This may be a manifestation of the slow growth rate characteristic of methane bacteria.

Perhaps the most interesting gas production activity was that liberating H_2 . Koyama (1964) reported H_2 in lake sediments, and Emery and Hogan (1958) detected H_2 in marine sediments. In the latter report it was assumed to have been produced by reaction of seawater with the sampling gear and so discounted.

We found H_2 production to dominate gas ebullition activities for a few weeks followed by rapid consumption to undetectable levels, presumably by microbial action (Fig. IV-4). Analyses on a waste bed 5-7 months old showed no detectable hydrogen (Table IV-4), a result consistent with this interpretation. The production of significant amounts in waste mixtures lacking free metals (Table IV-5) suggests that the reaction between seawater and metals proposed by Emery and Hogan (1958) does not account for the observation here.

On the basis of the foregoing it seems reasonable to generalize that gas production activity depends upon the nature of organic matter present and the stage of organic decomposition prevailing at the time of observation, the presence or absence of $\text{SO}_4^{=}$ as well as the presence or absence of metal

ions which can precipitate sulfides. Much of the variability of reported analyses can probably be explained in these terms as well as the amount of rejuvenated activity resulting from agitation associated with sampling activities.

Gas Production Rates

Tables IV-6 and IV-7 give gas production rates determined for various natural media, as well as our values for solid waste. These values represent maximum values observed while gas production occurred and cannot be extrapolated to long-term values; neither can it be assumed that the production of these gases occurred simultaneously. As mentioned earlier, our observations regarding H₂ production are not reported for comparable experiments or observations elsewhere. The value reported in Table IV-6 was determined for experiment at 25°C and is characteristic of high production rates observed in several others (suggested by the slope of curves in Fig. IV-2). At 8°C the rate was considerably lower, perhaps one or two orders of magnitude. Considering the temperature of bottom waters of the continental shelf or deep sea, the 8°C value is probably more significant.

A strong temperature effect is also indicated for CH₄ production by data of Koyama (1964) who

observed a variation of more than an order of magnitude with 20°C difference in incubation temperature. The values listed under "marsh gas" in Table IV-6 can probably be considered comparable to those listed under CH₄ (the major component of marsh gas). Field determinations by Conger (1943) and Emery (1969) are close to our value and are in the range listed by Koyama (1964) if the common assumption is made that activity is limited to the top 10 cm. The value found here is probably somewhat low because it was determined for very early stages of production. It seems reasonable to generalize that the CH₄ production rate falls in the range 0.5-5 ml Kg⁻¹ day⁻¹ for organic-rich sediments. The low value reported by Reeburgh (1969) was determined for an area which would be expected to have relatively low organic content.

The rate of H₂S production (Table IV-7) reported in the literature for sediment ranges from 0.014 to 19 mg L⁻¹ day⁻¹ (1.5 mg H₂S = 1 ml of gaseous H₂S). All values apply to temperatures of about 4-10°C. Our value (3.1) is high compared with those determined for deep arms of the sea, but falls in the range reported for Lake Solenoe which has a high organic input. A qualitative conclusion suggested by Table IV-7 which is consistent

Table IV-6. Gas production rates in natural and solid waste media. (Note units.)

H ₂	CO ₂	CH ₄	Marsh Gas	Remarks	Source
4.1 × 10 ⁻³ (25°)	400	0.4(05°)		Saturated paddy soils, (ml Kg soil ⁻¹ day ⁻¹) laboratory measurements.	Koyama (1964)
		1.0(10°)			
		2.4(15°)			
		3.8(20°)			
		7.5(25°)			
	52	4.24		Terrestrial landfill, (ml 100cm ⁻² day ⁻¹) <i>in situ</i> measurements.	Cal. State W.Q.B. (1967)
			0.63	Fresh sediments (ml 100cm ⁻² day ⁻¹) Summer (Maryland).	Conger (1943)
		0.027		Chesapeake Bay sediments (ml 100cm ⁻² day ⁻¹).	Reeburgh (1969)
			0.38	Brackish New England pond (ml 100cm ⁻² day ⁻¹) warm months.	Emery (1969)
1100(25°) 20(08°)		0.30(25°)		Seawater-saturated solid waste (ml Kg ⁻¹ day ⁻¹).	This report (see text)

Table IV-7. Estimated H₂S production rates in natural sediments and solid waste.

Rate	Comments	Source of Data
<i>Lake Sediments</i>		
(Crenogenic SO ₄ source)		
1-1.4	Lake Solenoe; 4 m depth; winter	Ivanov & Terebkova, 1959a
0.9-19	Lake Solenoe; temperature and organic input variable	Ivanov & Terebkova, 1959b
0.12	Lake Bielovod	Ivanov (1956 in _____ & Terebkova, 1959a
<i>Marine Sediments*</i>		
0.24	Calculated from Berner (1964), Santa Barbara Basin, 620 m	Fanning & Pilson (In press)
0.21	Calculated; Cariaco Trench, 1400 m	Fanning & Pilson (In press)
0.014-1.15	Black Sea, 180-2000 m	Sorokin (1964)
0.168	Calculated, Santa Barbara Basin	Kaplan, Emery & Rittenberg (1963)
<i>Solid Waste</i>		
3.1	Bed in running sea-water trough	This report (see text)

* All production assumed to occur in upper 10 cm (mg H₂S L. sediment⁻¹ day⁻¹).

with theoretical considerations is that the rate of H₂S formation is dependent upon the rate of delivery of organic matter to a SO₄⁼ rich environment. This statement is not at odds with the earlier idea that the amount of sulfide is eventually determined by the amount of SO₄⁼ available. The submergence of solid waste represents a locally rapid organic input and initially high production rates would be expected.

Bubble Formation

Gases produced in abundance and which do not enter into hydrolysis reactions are particularly likely to form bubbles. For this discussion, therefore, only H₂ and CH₄ need be considered. As described above, bubble formation and flotation problems were common in all experiments (which were con-

ducted at about one atmosphere pressure). At greater pressures more gas would dissolve and the tendency to form bubbles would be diminished. A thorough analysis of bubble formation requires attention to surface energies and effects of nuclei, both of which could have a large influence. Calculations along these lines would nevertheless remain tentative and the best answer would probably require direct observations on test bales at depth in the ocean.

A very rough estimate of the possibility of bubble formation can be gotten from a consideration of Henry's Law regarding solution of gases under pressure. Figure IV-5 graphically presents this principle using H₂ and CH₄ as examples.

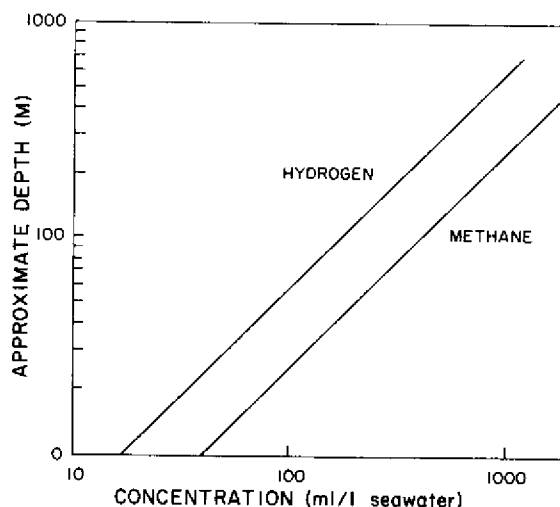


Figure IV-5. Henry's Law, an estimate of minimum gas concentration required to initiate bubble formation at various pressures or depths.

The solubilities at one atmosphere were determined using constants from Glasstone and Lewis (1960) and Atkinson and Richards (1967). The slopes of the lines are given by Henry's Law. In the results given in Fig. IV-4, 38 g of solid waste suspended in about 2 liters of seawater yielded about 260 ml of H₂. In a closed system this amount of gas could exist as bubbles to a pressure of about 5 atmospheres or a depth in the ocean of about 50 m. In a solid waste bale far less interstitial water would be available. Using the density of packing in the experimental trough, the same 38 g of waste would be associated with 130 ml of interstitial water. If 260 ml of H₂ were produced, bubbles

might form to a pressure of 120 atmospheres or roughly 1200 m.

In the case of either H₂ or CH₄ bubbles might occur if gas production rates are great compared with diffusive losses. A better estimate would therefore require diffusion rate calculations which, in turn, depend on specific characteristics of the bales under consideration. On the basis of production rates, however, bubble formation by H₂ represents a short-term likelihood and CH₄ a longer term likelihood.

Toxicity

Of the gases considered, only H₂S is toxic. It is considered comparable in this regard to hydrogen cyanide (Milby, 1962). H₂S reacts spontaneously with free oxygen and therefore has the added potential of creating an oxygen deficiency. The rate of this complex reaction is such that H₂S can co-exist with O₂, in a toxic capacity, for a duration of several hours (Richards, 1965b).

From the work of Theede *et al.* (1969), Fenchel and Riedl (1970), Adelman and Smith (1970), and Bonn and Follis (1967), it can be generalized that aerobic organisms cannot normally tolerate levels of H₂S in excess of from 0.004 to 1.5 mgL⁻¹. Theede (1969) states that no benthic macrofaunal species live in permanent metabolic contact with H₂S. Since we routinely observed concentrations of from about 1 to 150 mgL⁻¹ (Table IV-4) it is clear that the interstitial water would be toxic to aerobic biota even if it were diluted by 10² to 10⁴.

In many areas natural sediments also contain toxic levels of H₂S. Fenchel and Riedl (1970) characterized a "world wide" community of organisms occupying a layer of sediments adjacent to deeper H₂S containing material. The authors indicate that except for periodic "dives" into the H₂S

zone, organisms (except bacteria and protozoa) are limited to the oxygen-containing sediments. Where the distribution of H₂S in water or sediments is stable the biota are probably able to detect and avoid the area. Instances of mass mortalities have been reported where biogenic or plutonic H₂S is mixed rapidly into the water column (Brongersma-Sanders, 1957). Mortalities would probably result from solid waste-generated sulfides only if the interstitial water were "catastrophically" introduced into adjacent waters. Such an event could result from disruption of the accumulated solid waste beds by currents or collapse. Earthquake-induced gaseous release from H₂S rich sediments has apparently caused mortalities in bays and harbors (Brongersma-Sanders, 1957).

Summary

1. Model solid-waste beds and slurries suspended in seawater were analyzed for gaseous content.

2. At various states of decomposition, H₂, O₂, N₂, CH₄, CO₂ and H₂S were detected.

3. Initial gas production activity evolved large amounts of H₂; later CH₄ and H₂S were produced in lesser quantities.

4. In shallow water interstitial bubble formation is likely with associated buoyancy and ejection of pore water.

5. In deeper water the possibility of bubble formation, especially involving H₂ and CH₄, should not be discounted. Further attention to the question is required.

6. Highly toxic levels of H₂S were characteristic of interstitial water. The possibility of periodic rapid release of this water is a matter which should receive attention in baling considerations and dump site selection.

V. Oxygen Uptake by Solid Waste

Introduction

The possibility of oxygen depletion in overlying waters must be considered in any proposal to establish a deposit of organic matter on the sea floor.

Oxygen levels low enough to limit animal life occur naturally in limited areas of the world's oceans. Anoxic and oxygen-deficient waters are found in basins cut off from general circulation both by topography and water stratification; these include many fiords, the Black Sea, the Cariaco Trench of the Caribbean, and the basins off the coast of southern California. Oxygen may also become limiting in waters underlying areas of high productivity, such as the Benguela Current off southwest Africa and the Peru Current.

Eutrophication of estuarine and near-shore waters may lead to development of anoxic conditions in bottom waters when mixing is reduced by a thermocline or halocline. Fonselius (1969) describes the anoxic conditions of deep Baltic Sea water as self-perpetuating; when oxic water replaces anoxic, but nutrient-rich bottom water, the surface is fertilized. More organic matter is produced which settles and consumes oxygen in the basins.

Richards (1971) has stated that the "balance between oxygen supply and demand in the world ocean is precarious." In making this assessment Richards is dealing with large-scale phenomena such as the effect of limiting nutrients on the production of organic matter in major water masses.

This report is concerned with oxygen uptake by benthic surfaces rather than within the water column. Oxygen depletion in water immediately overlying waste may be possible in an area with extensive deposits, slow currents, and low initial oxygen levels.

In natural sea floor environments, oxygen is consumed directly by macrofauna, meiofauna, and microbiota. Large animals have very high respiratory demands on hard bottoms with rapid currents. Nixon *et al.* (1971) measured oxygen uptake by mussels of 2700 gm/m²/hr value. In infaunal communities the relative contribution of macrofaunal respiration is less than that of the meiofauna, microfauna, and microflora. Carey (1967) estimated that less than 17% of total respiration on a muddy bottom in Long Island Sound was due to macrofauna.

Deposits with a high concentration of easily degradable organic matter rapidly become anoxic be-

low the surface. In this environment, fermentative and sulfate-reducing bacteria produce reduced substances which may combine with oxygen if they diffuse to the surface or are exposed by mixing. This delayed biological oxygen demand is measured as COD.

In stable benthic deposits the potential oxygen demand of all contained organic matter is less important than the rate of oxygen uptake. Rate of uptake per square meter may be compared with the rate of exchange of overlying water to predict oxygen depletion.

A considerable body of research exists on oxygen uptake rates in a variety of sediment types carried out both in the laboratory and *in situ*. The same basic plan has been used in each experiment: a known surface area is enclosed in contact with a known volume of water, the water is circulated over the deposit, and oxygen concentration is monitored usually by oxygen electrode calibrated by chemical analysis.

In situ experiments preserve the chemical and textural structure of deposits and provide much more realistic estimates of oxygen uptake. The experiments reported on here were carried out on laboratory deposits which had been held in running seawater for extended periods. The chemical gradients and bacterial populations developed were, hopefully, like those which would be found in nature.

Considerable attention has been given to the relationship of the depth of a deposit to the rate of uptake from its surface. While Baity (1938) and Fair, Moore and Thomas (1941) found a positive relation between oxygen consumption and sewage sludge depth, several other investigators have found that uptake was independent in depths over 2-10 cm. (Edwards and Rolley, 1965; Stein and Denison, 1967; Hanes and Davison 1968; McDonnell and Hall, 1967.) This point is important in the design of test deposits and in the prediction of uptake rates for thick submarine deposits.

Methods

Initial oxygen uptake experiments were conducted in the large waste and control flumes sealed with glass and plastic covers (Fig. II-1). Surface areas and volumes were 0.933 m² and 181 l in the

waste flume and 0.962 m² and 272 l in the sand bottomed control flume. Submerged pumps circulated the water within the flumes and directed water over the temperature and oxygen probes.

The oxygen meter was calibrated by Winkler titration of samples taken before and after each run. Respiration in the water was measured in duplicate bottles kept at the same temperature as the flumes. Temperature was not controlled and usually varied several degrees during the course of an experiment.

A second series of experiments were carried out using smaller glass and PVC flumes (Fig. II-3) with 0.0813 m² of waste exposed and containing 4.4-4.7 l of water.

Test solid waste for these flumes was prepared in 12" × 3.5" × 2" blocks compressed with a specific load of over 300 lbs inch² and bound with a 2" grid of vinyl coated wire.

Three flumes each were prepared with waste containing 9.8 and 2.2% food. One flume each was filled with waste wrapped in perforated plastic, "stabilized" waste which had been held in salt water for six months, and clean sand.

A natural microbial community was allowed to form on the waste in flowing seawater. Initially high and low flow rates were used (2.7 cm/sec and 0.15 cm/sec). Later a high rate was used in all flumes.

During oxygen consumption experiments, a glass cover sealed the system. Circulation was provided by a peristaltic pump outside the flume. An oxygen probe and Winkler titrations were used as in the large tanks. Temperature control was provided by a flow of seawater over the cover.

Results

Oxygen uptake was measured in the large flumes on January 11-21, 1972, after test solid waste had been in place since November 5, 1971. The results of these experiments are shown in figure V-1. The points are corrected oxygen electrode readings. The rate of oxygen uptake in ml/m²/hr is shown next to each line segment. These were corrected for plankton respiration and adjusted for area and volume of each flume.

Oxygen consumption rates were relatively high during the first few hours of each experiment with

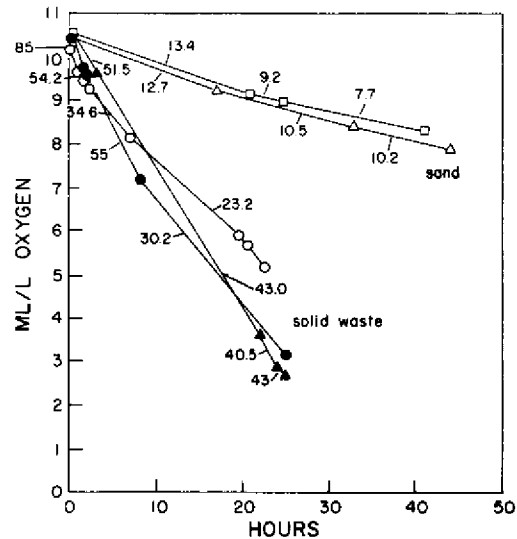


Figure V-1. Oxygen concentration in sealed 16' flumes containing test solid waste and sand. Oxygen uptake rates (ml/m²/hr) placed over line segments. Temperature range during experiments: sand 4.5-7.1°C, waste 3.2-7.5°C (see Figure V-4).

waste deposits (58-87 ml/m²/hr). It seems likely that this resulted from disturbance of the deposit and release of reduced substances. Other potential sources of error in these experiments are leaks which would result in low apparent consumption rates, and increasing temperatures during the experiments which would increase consumption rates. An error that could not be accounted for in these experiments was the effect of H₂S on oxygen titration values. Each ml of H₂S in solution reduces the indicated oxygen concentrations by 2 ml. Although this may be thought of as representing the oxygen which would eventually be consumed by oxidation of the sulfide, sulfide determination and correction of oxygen values will be carried out in future experimental work.

After the initial high rates of oxygen consumption in the waste flume uptake ranged from 23-55 ml/m²/hr. These values are considerably lower than rates in the control flume of between 10.2 and 13.4 ml/m²/hr.

The results of experiments conducted in small flumes are shown in figures V-2 and V-3. Test waste was placed in these flumes March 27-31, 1972.

During April 16-22 water temperatures were 7-9°C. The curves of oxygen concentration are concave upward but show less initial drop than in the large flumes. The uptake rate for complete ex-

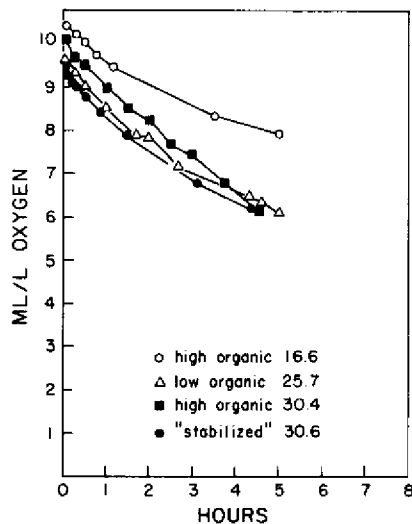


Figure V-2. Oxygen concentration in sealed 4' flumes containing test solid waste. Waste description and oxygen uptake rate ($\text{ml}/\text{m}^2/\text{hr}$) over course of the experiment placed next to consumption curve. Temperature range during experiments was $8-9^\circ\text{C}$.

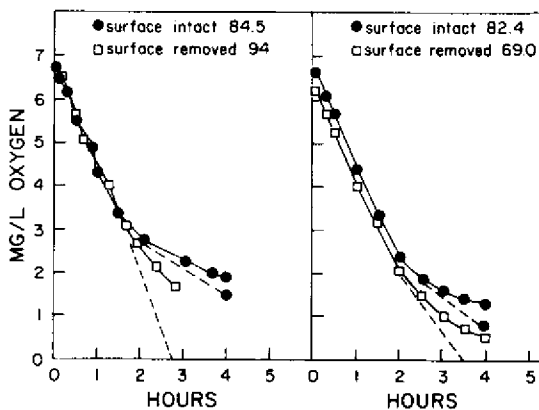


Figure V-3. Oxygen concentration in sealed 4' flumes containing high organic matter waste with bacterial surface film intact and removed. Connected points are oxygen electrode values; Winkler titration values are connected by dashed lines. Oxygen uptake rates ($\text{ml}/\text{m}^2/\text{hr}$) are given for oxygen concentration of over $3 \text{ mg}/\text{l}$. Temperature during experiments was 17°C .

periments was between 16.6 and $30.6 \text{ ml}/\text{m}^2/\text{hr}$. "Stabilized" waste had rates very nearly the same as high and low organic matter waste.

In June water temperatures were $16-17^\circ\text{C}$. Plankton respiration was $.05-0.1 \text{ mg}/\text{l}/\text{hr}$ where it had been negligible in the April experiments. The oxygen consumption of two high-organic matter deposits were measured both with a well developed

bacterial film left intact and with the film removed.

During the first two hours the oxygen concentration declined at a rate of between 70 and $90 \text{ ml}/\text{m}^2/\text{hr}$, considerably higher than at lower temperatures. At oxygen levels below $3 \text{ mg}/\text{l}$ the rates decreased in all experiments. The decline was most marked in the flumes with an intact bacterial film. Oxygen titration values determined at the end of each experiment were lower than the oxygen electrode values. In the flumes with bacterial film removed titration values were zero.

H_2S levels were determined at the end of each experiment. The flumes with bacterial films contained $1.5-2$ and $2.2 \text{ mg H}_2\text{S}/\text{l}$; the flumes with film removed contained 5.8 and $6.0 \text{ mg H}_2\text{S}/\text{l}$.

Discussion and Projections

Hargrave (1969) determined benthic oxygen consumption of a number of lakes and assembled other oxygen uptake values from a variety of aquatic environments. When these rates are graphed against temperature on a log-log scale they cluster around a straight line. He considered this to be a result of the effect of temperature both on diffusion and on organic metabolism. Figure V-4 shows the regression line of values from both fresh water and marine environments. Selected values from marine environments are shown separately. Oxygen uptake rates determined in three studies on sewage sludge and wood pulp deposits in seawater are also placed on this figure.

The rates measured during the experiments in the large flume are shown by connected points (1a, b, c, 2a, b). The control flume rates fall close to the regression line. The rates for the waste flume are high for the temperature at which they were measured. While this may reflect the presence of cold-adapted microflora on the waste surface, it is more probable that this represents a high rate of diffusion of reduced compounds from within the deposit.

The rates measured in the small flumes are near the regression line. They are higher than in many natural communities and are very near those reported in other waste deposits.

In the experiments conducted at 17°C rate of uptake decreased at low oxygen concentrations. This indicated that a significant portion of the uptake was related to diffusion of oxygen into the

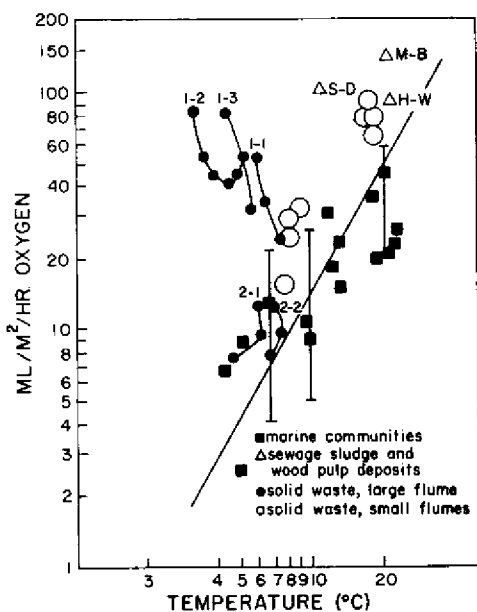


Figure V-4. Oxygen uptake rates of benthic surfaces as a function of temperature. Rates and ranges from marine benthic communities and regression line from Hargrave (1969). Additional rates from marine communities from Blake and Jeffries (1971) and Smith et al. (1972). Rate for in situ pulp deposits (S-D) from Stein and Denison (1967). Rates for laboratory sewage sludge deposits (H-W) from Hanes and White (1968) and laboratory wood pulp deposits (M-B) from Martin and Bella (1971). Rates from large and small flumes from this study.

bottom since diffusion of reduced substances from the bottom is independent of oxygen concentration (Martin and Bella, 1971).

The importance of diffusion of reduced substances from these deposits is illustrated by increased rates of oxygen uptake and H_2S concentration in the experiments where bacterial films were removed (Figure V-3). These films probably act as both physical and biochemical barriers to H_2S diffusion. It would be particularly interesting to determine the efficiency of these layers in "processing" H_2S and oxygen.

During oxygen uptake experiments, materials enter the overlying water which exert biological and chemical oxygen demand over periods longer than the duration of the experiments. Each mole (or ml) of H_2S released into the water will combine with 0.5 and 2 moles (or ml) of oxygen in the process of oxidizing to sulfur and sulfate. Thus 5.8 ml of H_2S measured at the end of an experiment could ultimately combine with a volume of oxygen three

times that present in the water in the experimental chamber.

Dissolved organic compounds diffusing from waste deposits are metabolized by bacteria in the water column. Martin and Bella (1971) discuss the effect of the release of substances with differing reaction rates on the BOD of water overlying waste. They conclude that only the slower reacting materials will be detected in the BOD test. They propose that detailed studies should be made of the small interfacial area between sediment and water in regards to the transfer mechanisms of oxygen and BOD. Empirical determination of H_2S oxidation rates would be an important adjunct to such studies.

The direct oxygen consumption of benthic deposits with a high concentration of organic matter proceeds at rates up to ten times those in natural infaunal communities. Nevertheless, the rates from wood pulp sludge in well mixed water (140-212 $ml/m^2/hr$ at $20^\circ C$) (Stein and Denison, 1967) are not much higher than those of some natural infaunal communities. This rate is much lower than that measured in some epifaunal communities such as oyster reefs and mussel beds (300 and 1900 $ml/m^2/hr$) (Nixon *et al.*, 1971).

This apparent upper limit of oxygen uptake from surfaces can be used in assessing the possibility of oxygen depletion over a waste deposit. Since low temperature at actual dump sites would retard bacterial activity, a rate of 150 $ml O_2/m^2/hr$ would be a high estimate of maximum direct uptake rate. A slightly higher rate might be assumed to account for the oxygen demand rates of diffusing reduced substances and organic compounds.

Oxygen depletion at proposed disposal sites could be estimated on the basis of O_2 content of the water, O_2 consumption rate of waste deposits, current velocities, and diffusion velocities. Diffusion velocities appear to be particularly difficult to determine, even to an order of magnitude (T. T. Polgar, pers. comm.). Examination of near-bottom profiles of oxygen and dissolved materials regenerated from the sea floor may provide information on vertical mixing rates in the deep sea.

Dense infaunal communities significantly increase the rate of oxygen uptake in polluted areas (Knowles, Edwards and Briggs, 1962; Cox, 1970). Although tube-dwelling polychaetes colonized the test waste (see section VI), it is not known to what extent colonization would take place in deeper wa-

ter. Infaunal species occupying anoxic sediment maintain an oxic environment within their burrows and tubes. They shift the oxic-anoxic boundary to a locus within the sediment. The permeability of various tubes to H_2S and dissolved organic substances and the levels of toxic substances within the tubes are of great biological interest in both polluted and non-polluted environments.

Suggestions have been made that waste be dumped in areas of high sedimentation. McKeown, Benedict and Locke (1968) found that burial of wood-pulp sludge with a 1.7 cm sand layer reduced oxygen uptake by 35-43 percent. The mechanism involved in this reduction is not clear since sand should not affect the diffusion rates of dissolved substances out of a deposit. A covering could reduce the rate of oxygen transfer to aerobic microorganisms on the sludge surface, however. A covering of

sediment with a high diffusion coefficient relative to the waste would tend to remain oxic while a layer with a lower rate would become anoxic.

"Stabilization" of sludge deposits is said to have occurred when BOD is undetectable. It usually means that easily degraded materials have been metabolized and that only resistant material is left. No stabilization was detected in test waste after 4 and 10 months. This could be an effect of low average temperatures, relatively high initial food content, or slow breakdown mediated by the internal environment of the deposits. The extent to which cellulose is being degraded in these experiments is unknown. It is possible to state however, that at cold bottom temperatures and with massive waste bales, the period of oxygen consumption at an actual dump site will be prolonged over years.

VI. Reactions of Organisms to Waste Deposits

Solid waste deposited on the sea floor is a potential site for colonization by microbes and both epifauna (fouling animals) and infauna (burrowing animals). Microbial populations degrade waste materials; provide food for animals; and serve as indicators of levels of dissolved organic matter, hydrogen sulfide, and oxygen. Animals may either bind or disaggregate the waste surface. The absence of animals indicates the presence of toxic or repellent substances. Fouling fauna can serve as food for predators including fish.

A series of experiments on waste deposit organism interactions were carried out in flow-through tanks described in chapter II. Most of the observations reported on here were made in tanks with unwrapped solid waste. They were more biologically interesting than plastic-wrapped blocks and could represent both unwrapped bales as well as broken packaged bales. The waste in the large flow-through tanks was considerably less compact than a newly compressed waste block. The methods and results for observations on microbial, epifaunal, and infaunal colonization are discussed separately although a great deal of overlap exists. General conclusions and projections are presented at the end of this section.

Observations and Experiments

Microbial colonization

There is enough organic matter in seawater to support bacterial growth on any solid substrate. It has been suggested that the formation of a bacterial slime layer must precede setting of fouling fauna on a clean surface. The microbial colonies which grew on solid waste surfaces were not merely slime layers; they consisted of thick gelatinous or felt-like colonies which often covered the surface of the deposits. These formed in all flow-through tanks and have been observed in a shallow ocean test bale by G. Rowe (pers. comm.).

These layers are difficult to describe quantitatively, because they responded to small changes in flow rate in the tanks. The following description of surface types integrates several series of observations. Tentative identification of some forms were provided by Dr. J. McN. Sieburth.

Initial surface: The milled paper used in these experiments had a "fluffy" appearance caused by

cellulose fibers. Unwrapped waste surfaces provided effective traps for suspended material even at high flow rates. This produced a brown floc consisting of mineral matter, fecal pellets of copepods, diatoms, and particles of red algae. Sedimented material collected from flow-in and flow-out aprons consisted of 11-15% volatile matter. Deposition rate was 0.6-0.3 gm dry weight/M²/day at the up and down stream ends of the tank.

Thiobacterium pellicle: By the end of two weeks both at summer and fall temperatures (20°C and 9°C) heterotrophic bacteria had formed a translucent coating over the waste surface. A species tentatively identified as *Thiobacterium bovista* was very noticeable among these because of its characteristic "puff balls" 1-5 mm in diameter. The presence of this species indicated that H₂S was reaching the deposit surface. Aerobic and microaerobic heterotrophs initially growing within the deposit became restricted to the surface when oxygen was depleted within. This took place within 6-7 days at 10°C in closed tanks (see chapter III). This pellicle was relatively weak; in a single test it was eroded by current velocities of 6 cm/sec (Table VI-1).

Table VI-1. Resistance of microbial films to erosion.

Surface Type	Velocity at Initiation of Erosion (cm/sec)	Tank Dimensions	Number of Tests
Initial (2 days)	9-12	48" × 4"	5
<i>Thiobacterium</i>	6	48" × 4"	1
Aerobic mat	20	16' × 2'	2
Sulfide mat	17, 20, 22	16' × 1'	3
Sulfide veil	1	48" × 4"	3
		(36" test area)	

Aerobic mat: High H₂S concentrations are found in deposits more than a few weeks old. The appearance of the deposit surface depends on the vertical position of the O₂ - H₂S interface. At current velocities of 1-2 cm/sec and above, this interface occurred 1-2 mm below the surface. This oxidized surface was brown-colored from sedimented material as described on the initial surface. A diverse microbiological community including fungus created a felty mat with paper fibers. Harpacticoid copepods

fed on the mat. It was difficult to achieve controlled high water velocities in the tank in which this surface was best developed; however the surface appeared to be quite strong remaining intact at velocities of about 20 cm/sec.

Sulfide mat: When water velocities were between 0.1 and 1 cm/sec the sulfide zone reached the deposit surface and a dense mat of sulfide oxidizing bacteria formed. These were mainly members of the order *Beggiatoales*, colorless forms related to blue green algae. The genera *Beggiatoa*, *Thiothrix*, and *Vitreoscilla* occur in long chains or trichomes. *Thiothrix* and *Vitreoscilla* become attached to surfaces; their trichomes formed a free-swinging "fur" up to 1 cm long. *Beggiatoa* and *Vitreoscilla* have gliding mortality and can cover new surfaces in a matter of hours. These trichomes formed tangles around and through organic particles. Another sulfide oxidizer, *Achromatium*, formed colonies on waste surfaces throughout the winter (0-10°C).

After three months at ambient seawater temperatures, tank 1 had developed a thick mat of successive bacterial layers. Erosion of this mat took place at 17, 20, and 22 cm/sec. Linear strips of the surface ripped off in some cases; in others several layers were removed one at a time.

Sulfide oxidizer mats formed over the perforations in plastic-wrapped bales. In some cases these colonies spread laterally over the plastic.

Actinomycetacea: During April and May blue-white "fluffy" masses of an actinomycetacid species dominated tank 3 and a 48" x 4" tank of year-old waste. When this growth was removed from the deposit surface it would grow to a depth of 1 cm in 2-3 days. The new growth was "clean" for a few days before it was colonized by ciliates and harpacticoids. These colonies had little erosion resistance and would probably not be found in such a form in the ocean environment.

Sulfide veil: When flow was shut off, the water over the bottom became anaerobic and the oxygen H₂S interface rose above the bottom. A "veil" of microaerobic sulfide oxidizing bacteria accompanies this interface, a phenomenon familiar in stagnant salt water aquariums. It seems improbable that such a veil could form in the ocean unless stability was induced by a strong chemical or tem-

perature gradient. When the water over a deposit surface became anoxic, aerobic and microaerobic organisms died or left the deposit. Recolonization and regrowth took place after circulation was restored.

Animal Fouling

Non-quantitative observations were made on fouling growth on waste surfaces throughout these experiments. Quantitative observations were made on two series of fouling surfaces placed in tanks 1 and 2. Water velocity in these tanks was usually less than 1 cm/sec.

Series 1 (November-January): Duplicate 1" x 3" slides of glass, plastic (PVC, polyethylene, and polystyrene), tinfoil, and pine wood were placed at upstream and downstream ends of both waste and control flumes. The slides were placed with one end penetrating the waste surface. The slides were examined and replaced after 1, 3 and 8 weeks.

Few larvae were available at this time and colonization by larger forms was very limited. No upstream-downstream effects were noted. The glass slides showed the greatest differences between waste deposit and control. On the control slides (4) there were an average of 25 *Vorticella* colonies (stalked ciliate protozoans) while there were none on the waste slides. The tube-building polychaetes *Polydora* and *Spirorbis* also colonized the control slides.

The slides from the waste tank had a gelatinous coating along the deposit-water interface. The lowest part of the slide was colonized by nematodes; harpacticoid copepods were found at a higher level. Most of the slide was covered with a "fur" of white sulfide bacteria. Flatworms (*Turbellaria*) were abundant in the bacterial zone.

The metal slides had very little fouling, but were cut through by corrosion at the sediment-water interface in both tanks.

Series 2 (March-September): This series consisted of 2 racks of 5 glass and 5 plastic slides in each tank. They were examined and replaced after two weeks and removed in September for detailed examination.

After nearly six months neither waste nor control tank slides were heavily fouled. It had been hoped that mussels and barnacles would settle in these

tanks, but darkness, low water velocities or other causes prevented this. Nevertheless there were large differences between the fouling communities of both plastic and glass in the 2 tanks.

The slides from the waste tank were dominated by attached filaments of sulfide bacteria. The presence of many species of ciliates, a distinctive oligochaete, nematodes, and 3 species of harpacticoids could be correlated with high levels of organic matter and bacteria and low levels of oxygen. Mature hydrozoans, 2 species of tunicates (sea-squirts), and other species were found on both the waste and control slides indicating that some normal fouling species can tolerate H_2S and other dissolved materials from test solid waste.

The control tank had more Foraminifera, *Spirorbis*, and *Vorticella* than the waste tank. In the control tank there was also a noticeable difference between glass and plastic slides; the (polystyrene) plastic slide had a thicker accretion of animals and sediment including hydrozoans and several unidentified forms.

Heavy fouling by *Molgula manhattensis* (sea squirt) took place in the inlet end of the waste tank but ended abruptly where the waste deposit began. Apparently the water quality within the tank prevented settlement or growth.

Mytilus edulus (edible mussel) settled and grew on hard packed waste in the 48" x 4" tanks. The water velocity in these "high flow" tanks was about 2.7 cm/sec, high enough, presumably, to both dilute pollutants and provide food and oxygen. These animals withstood temporary periods of exposure to low O_2 and high H_2S concentrations when flow was decreased. This is consistent with the results of Theede *et al.* (1969) who reported a high tolerance of *Mytilus* to low O_2 levels.

Colonization by Infauna

The solid waste deposit in tank 1 was exposed to colonization by larvae of both fully marine and estuarine species for nearly a year. Although the salinity of the water in the tanks remained near 33 o/oo, nearby areas supplied larvae of brackish water species. Water was pumped only about 200 feet through an all-plastic system before it reached the experimental tanks.

The rate of colonization in the control tank was low indicating that natural sea floor had not been successfully modeled. Low flow rates and subse-

quent deposition of fine sediments were likely reasons. Since it is impractical to pump the large volumes necessary to prevent deposition in such tanks, it is suggested that in future experiments energy could be added to such systems by generating waves. Increased circulation within tanks would keep fine materials in suspension and provide an environment suitable for filter feeding epifauna.

Capitella capitata was a consistent colonizer of solid waste deposits. This species is a familiar indicator of organic pollution and low O_2 levels (Reish, 1966). It is also an opportunistic colonizer of unpolluted sediment from which other animals have been removed (Sanders *et al.*, 1972). Loose aerobic waste was colonized in October-November 1971. Tank 1 and several 48" x 4" tanks were colonized during spring and early summer, 1972. In late summer of 1972 *C. capitata* was replaced in tank 1 by *Nereis succinea*. Tank 3, which had a lower flow rate and higher H_2S concentration than tank 1, supported a dense population in September 1972 (about 13,600/m² representing 20 gm/m² dry weight). *C. capitata* occupied tubes extending up to a cm above the sediment surface. They fed on the surface ingesting both the bacterial mat and surface sediments. The surface of the waste developed a deposit of their characteristic 1.0 x 0.6 mm fecal pellets. These consisted mainly of sediment although a fraction was made up of paper fibers. *C. capitata* can survive for days at concentration of H_2S up to about 30 mg/l (Jacubowa and Malm, 1971 in Theede *et al.*, 1969). The H_2S concentration in tank 3 of .2-4 mg/l was well below this. *C. capitata* was not found in the control tank.

Neanthes (Nereis) succinea is extremely abundant in soft or peaty bottoms of brackish estuaries. It is larger than *C. capitata* (about 5 cm). It burrows deeply and may have several openings to the surface. These burrows are not lined. *N. succinea* colonized tank 1 during the late summer of 1972. Individuals fed on the bacterial mat, developing radial patterns around their burrows. Their burrows could be seen through the window in the wall of tank 1 extending at least 15 cm into the deposit. Species of *Neanthes* have been reported to be able to live at 20 mg/l H_2S (Hecht, 1932 in Theede *et al.*, 1969) while *N. diversicolor* had 50% mortality in 6.7 mg/l H_2S at 96 hours. The H_2S concentration in the waste deposit was over 300 mg/l in September. The worms are exposed to much lower H_2S levels

since they pump surface water through their burrows. A white lining of sulfide oxidizing bacteria demonstrates that the sulfide-oxygen boundary is at the walls of the burrows.

The only other large species found in tank 1 was *Harmothoe* (scale worm), a genus found under rocks and in some oxygen deficient basins (Demel and Mulicki, 1954 in Theede *et al.*, 1969).

Polydora ligni, a small tube dwelling polychaete, colonized some the 48" x 4" tanks and the plastic-coated bales in the 18' diameter tank. The resistance of *Polydora* to H₂S is not known; however, Richards, 1969 (in Dean, 1970) found 50% survival at 10 days in 1.5-2.5 ppm O₂.

The most successful colonizer in the control tank was the detritus-feeding polychaete *Amphitrite* (*johnstoni*?). Approximately 20 large individuals were distributed evenly throughout the tank. *Pherusa affinis* was common and a nemertine worm and a sponge (*Haliclona*) were also present.

No mollusks or crustaceans colonized either control or test tank; the sponge was the only filter feeder found.

Reactions of Benthic Animals Placed in Contact with Waste

When milled paper is suspended in seawater in low density, "slurry" is formed (less than 2% paper by weight). Such slurries could be found down stream from an eroding waste deposit. Bivalves buried by this material would not be able to burrow upward through it because of its low density. Observations were made on groups of bivalves buried by a layer of waste slurry 5 cm thick.

Pitar morrhuana (associated with fine sediments) and *Mercenaria mercenaria*, the hard clam, extended their siphons through the deposit to the surface. Filtering rates as indicated by pseudofeces (suspended material filtered from the water and expelled rather than being ingested) production remained high over the one-month observation period.

Arctica islandica, a large offshore species without siphons "blew" the waste away from the immediate area with its powerful excurrent flow, and during expulsion of pseudofeces through its incurrent aperture became covered with a layer of pseudofeces.

Shrimp of the genera *Palaemonetes* and *Crangon* moved easily over slurry surfaces.

Ampeliscid amphipod crustaceans are important offshore species occupying tubes extending above the sediment surface. When *Ampelisca agassizi* from Rhode Island Sound were buried by 2 cm of slurry, they burrowed through the waste, and swam to the surface of the water.

A number of *Neanthes virens* (polychaetes) 8-10 cm long were placed in dense anaerobic waste in a flow-through tank. They made burrows and fed at the surface, producing fecal pellets containing paper fragments.

Bioassays

It is difficult to design a meaningful bioassay of solid waste eluates because of the unknown degree to which materials diffusing out of the deposit will become diluted by overlying waters. Diffusion rates out of the waste will be in the range of rates from sediments (less than 10⁻⁵ cm²/sec) while characteristic vertical dispersion in the ocean can vary from 1-10 cm²/sec. Horizontal dispersion rates are orders of magnitude larger. This disparity in rates would be even greater with wrapped bales. In general the toxicity of interstitial waters to colonizing infauna may be more important than the toxicity of eluates in overlying water.

A group of representative animals were screened for sensitivity to eluates by holding them for 72 hours in a flow-through system. Fully marine species were used when possible to avoid the criticism that estuarine species are resistant to pollutants. One species, *Arctica islandica*, was held for longer periods directly on a deposit of waste.

Method: Eluate was generated in tank 3 containing a shallow water layer over 2.5 m² of waste. The waste had been in place for six months when the assays were begun and was covered with a dense mat of sulfide bacteria. The residence time of water in the tank was about 19 minutes. The eluate was distributed into 5 one-gallon glass bottles at a flow rate of 0.4 gallons/minute per bottle. Tests were made at ambient temperature. In most cases single individuals were tested; barnacles and mussels were tested in groups. Controls were left in running seawater and test animals were returned to running seawater for a week after exposure to eluate. Oxygen was always present in the eluate, usually more than 4 mg/l H₂S levels were variable, falling between 0.17 and 3 mg/l.

Results and Discussion: The results of these tests are shown in Table VI-2. The single fish species used (the cunner, *Tautoglabrus adspersus*), was by far the most sensitive animal tested, none lived more than 2 days. It does not seem necessary to seek a cause of this mortality other than H₂S. The following values show the high toxicity of H₂S for fish. Channel catfish fingerlings were killed by 0.8 ppm at pH 6.8 (Bonn and Follis, 1967), sockeye salmon smolts showed distress at 0.3 ppm and died at 2.3 ppm in 20-25 minutes (Servizi, 1971). Herring (*Clupea harengus*) and sole (*Solea solea*) died in 6 and 24 minutes respectively in 7.6 ml/l (Shelford and Powers, 1915). No mortality was observed in fish held in standing waste eluate without aeration. This indicates that the toxic material or materials were utilized by microorganisms, oxidized or adsorbed with time.

The only other mortality recorded during 72 hour tests occurred in shrimp (*Crangon*). Theede *et al.*, 1969 (Table VI-4) showed that *Crangon* and other crustaceans were much more sensitive to oxygen depletion than other groups tested. Unfortunately their tests of H₂S toxicity were carried out in oxygen-depleted water and it is not possible to determine mortality due to H₂S alone. The H₂S sensitivity of some planktonic copepod crustaceans have

been determined by S. Vargo (unpublished). She found that in 2-hour tests with oxygen absent *Acartia tonsa* and *Eurytemora affinis* were killed by .032-.064 and 1.28-1.6 mg/l H₂S respectively. Although copepods are not closely related to shrimp these results do illustrate the generally sensitive respiratory mechanisms of crustaceans.

Bacterial fouling was an unusual problem resulting from exposure to waste eluate. Filaments of sulfide bacteria suspended in the eluate became attached to the walls of the bioassay bottles, bivalve shells, and crustacean exoskeletons. Barnacles were heavily fouled; after 72 hours in eluate their filtering movements were slow and erratic. Although no mortality was observed in these tests, interference with both feeding and respiration may have eventually caused mortalities. When the barnacles were transferred to clean water the bacteria died back in a few days and the barnacles regained their filtering ability.

Arctica islandica, a large bivalve found across the continental shelf, was extremely resistant to eluate. This agrees with Theede *et al.*, 1969 who found that at 10°C in 0.15 ml/l O₂ and 6.7 mg/l H₂S 50% mortality did not occur until 800-1000 hours. This resistance was not due to shell closing

Table VI-2. Results of bioassays, 72 hours other than *A. islandica*, flow-through unless marked.

Species	Temperature °C	H ₂ S Concentration	Number Tests	Time to Death
<i>Tautoglabrus adspersus</i> cunner (7.4-10 cm) rocky shores and bottoms to 35 fathoms	13-19	0.2	18	10 dead in 24 hrs
			9	all dead in 48 hrs (batch) none dead
<i>Balanus balanoides</i> barnacle	13.5-14.5	0.2	200 (20/group)	none dead
<i>Pagurus pollicaris</i> deep water hermit crab	19	0.2	10	none dead
<i>Crangon septemspinus</i> shrimp	18	0.2	10	6 dead in 72 hrs
<i>Cancer irroratus</i> rock crab	16-19	.17-.26	15	none dead
<i>Mytilus edulis</i> edible mussel	19-21	0.2	50 (5/group)	none dead
<i>Spisula solidissima</i> surf clam	15	0.17	5	none dead
<i>Arctica islandica</i> ocean quahog	3-5	—	24	27 day 4 dead
	14.5	1.3	10	30 day none dead
	17	0.2	10	7 day none dead

and use of anaerobic metabolism since *Arctica* also had tissue resistance to low O₂ and high H₂S.

Table VI-3 shows an increase in sensitivity to low O₂ and high H₂S from mollusks, to polychaetes and echinoderms, to crustaceans. In nature polychaetes appear to be most characteristic of waters and bottoms containing H₂S, however. Several have specialized behavior or physiological adaptations to constant presence of H₂S. The toxic effect of H₂S is a result of its combination with metal-containing enzymes in respiratory pigments. The deep-burrowing lug worm (*Arenicola marina*) has hemoglobin which does not combine with H₂S (Patel and Spenser, 1963).

Table VI-3. Resistance of invertebrates to very low oxygen levels (0.15 ml/l) and to 6.7 mg/l hydrogen sulfide at low oxygen levels. Temperature 10°C (after Theede *et al.*, 1969).

Baltic Sea Individuals Tested at 15 o/oo Salinity	50% Mortality after Exposure Time in Hours Listed	
	Low Oxygen	H ₂ S + Low Oxygen
<i>Arctica islandica</i> —bivalve	1320	800-1000
<i>Mya arenaria</i> —soft shell clam	504	408
<i>Nereis diversicolor</i> — polychaete	120	96
<i>Asterias rubens</i> —sea star	84	67
<i>Ophiura albida</i> —brittle star	32	30
<i>Carcinus maenas</i> —crab	48	32
<i>Gammarus oceanicus</i> — amphipod crustacean	15	8
<i>Idotea baltica</i> —isopod crustacean	6	8
<i>Crangon crangon</i> —shrimp	2	2
North Sea Individuals Tested at 30 o/oo Salinity		
<i>Mytilus edulis</i> —mussel	840	600
<i>Cardium edule</i> —bivalve	102	96

Sulfide may occur as H₂S, HS⁻ and S⁼. At low pH the un-ionized form, H₂S predominates. Baas-Becking and Wood (1955) and Theede *et al.* (1969) state that un-ionized sulfide is less toxic than the other forms. Adelman and Smith (1970) and Bonn and Follis (1967) present data from experiments with fish which show just the opposite. This is an important point since pH is usually reduced in interstitial water.

Ammonia was present within the waste deposits

and occurred at slightly higher than background levels in eluates (maximum 0.06 mg/l). Ammonia toxicity increases tenfold with a pH increase from 7 to 8. Burrows (1964) found gill abnormalities in salmon fingerlings exposed 4 weeks to 0.3-0.7 ppm ammonia at pH 7.8. This can be taken as a conservative estimate of minimum harmful levels. Other potentially toxic substances in eluates were not determined. These could have included fungicides in paper and volatile organic compounds resulting from anaerobic fermentation. Hydrocarbons, pesticides, and metals other than tin cans were not added to the test waste.

Behavioral Responses to Solid Waste

A number of soluble substances were measured in interstitial water and eluates from waste deposits. The occurrence of many additional compounds can be predicted on the basis of knowledge of materials added and degradation processes. Observations were made on the effect of waste fluids on food-sensing responses of three decapod species and on movements in relation to a test bale of two species.

Food sensing: Many marine animals show stereotyped responses in the presence of soluble food. These responses have been used to study the detection and preference of chemical substances by a variety of animals including lobsters (Shelton and Mackie, 1971), mud snails (Gurin and Carr, 1971), and a polychaete, *Diopatra* (Mangum and Cox, 1971). These responses are less affected by extraneous clues such as light than are movements within a "choice chamber."

Observations were made on the responses of *Cancer irroratus* (rock crab), *Pagurus pollicaris* (hermit crab) and *Homarus americanus* (lobster). Individuals were exposed to: (1) gauze pads soaked in interstitial water from a waste deposit which had been in place over six months and (2) a weak flow through a hose of eluate from tank 3. Animals were kept in tanks for several weeks after capture, then starved 3-7 days before testing. Single lobsters were used in two or more trials with at least 3 days between trials, the other animals were used only once. For each species 10 observations were made of responses to fresh clam juice, 15 observations were made of response to interstitial water, and 5 observations were made on response to eluate.

All species tested reacted strongly to clam juice.

They "unfolded" their antennules immediately after it was added and performed rapid flicking movements. Maxillipeds were spread and waved. Lobsters and crabs moved about their tanks.

Interstitial water and eluate created little response. Although antennules were placed in the sensing position, flicking occurred in no case. There was little movement of maxillipeds and no walking. There were no attempts to feed on the gauze pads when they were presented.

Movements around a test bale: Observations were made on the movements of lobsters and crabs in an 18' diameter tank containing a tray of solid waste with a perforated plastic cover. A sand-filled plastic covered tray served as a control. The bottom of the tanks was covered by a thin layer of sand. Four animals were used at one time. It was hoped that low density (1 animal per 5.8 m²) would reduce encounters and allow normal movements. Illumination was kept dim by an opaque cover. Observations of 15 minute duration were made from a catwalk over the tank after animals had been held a week.

Lobsters were observed on five occasions. They occupied shallow pits around the perimeter of the tank and moved infrequently during the day. Tracks indicated that they spent a great deal of time walking around the perimeter. Fine sediment and bacterial films on trays were not disturbed indicating that the lobsters had not climbed up onto them.

Rock crabs were observed on nine occasions. They were active during the day and spent most of their time feeding by working through bottom sediments. They showed a tendency to maximize distance between individuals. They did not climb onto either tray. Tracks were most heavy around the perimeter of the tank, less heavy around the test trays, and scattered across the tank floor. Feeding took place in open areas. No difference in track density was detectable between the areas around test and control trays.

Discussion: The negative results of these experiments can be partially explained by reference to Table VI-4, a summary of some recent experiments on responses of benthic animals to chemical substances.

In general the substances most attractive to predators and scavengers were those which are abundant in the fresh body fluids and tissues of

animals. Some predators of bivalves may be attracted by prey excretory products such as ammonia and repelled by fresh body fluids. Amino acids are particularly attractive. In the case of several decapods, mixtures have a greater effect than high levels of single constituents. Non-fresh animal products were rejected (old blood—Mangum and Cox, 1971) or ignored (putrid cod extract—McLeese, 1969).

Although the waste interstitial water contained no less than 1200 mg/l of dissolved organic matter it appears that substances inducing positive feeding responses are not present. Other than 2% "carbohydrate," the makeup of this material is not known. High concentrations of short chain organic acids are characteristic of materials undergoing anaerobic fermentation. Volatile substances with strong odors were very noticeable in waste deposits. Volatile acids were repellent to *Diopatria* (Mangum and Cox, 1971). In tests with eluates they have caused no effect or have had a masking effect.

Hydrogen sulfide was present in both interstitial water and eluate. Although no rejection or escape behavior in relation to H₂S was observed in these experiments, it is probably detectable by marine animals in sub-toxic concentrations. Ishio (1965) found that the ratio of the median avoidance concentration to the lowest lethal concentration of H₂S was 1.4 in several freshwater fish. Although Sheldford and Powers (1915) have reported avoidance of H₂S by sole, sculpin, and herring species, the limits of detection and behavioral effects of H₂S on marine species are poorly known.

General Conclusions and Projections

In laboratory models of a submarine waste deposit several conditions were observed which would affect organisms. These may be examined with reference to possible ocean dumping sites and to the design of further field and laboratory experiments.

Oxygen Levels

Oxygen will be consumed within a waste deposit even if microbial activity is low due to low temperature and high pressure (chapter III). Oxygen will probably not be reduced in the water overlying the deposit, however, due to limits on the rate of uptake of a surface (chapter V) and initial high

Table VI-4. Response of benthic animals to some chemical substances.

	Organism	Chemo-Response	Source
Coelenterates	<i>Anthopleura elegantissima</i> (sea anemone)	Asparagine causes food to be brought to the mouth; glutathione causes it to be ingested.	Linstedt (1971)
Crustaceans	<i>Carcinus maenas</i> (green crab)	Attraction to mixtures of amino acids, nucleotides, and organic acids greater than attraction to any one component.	Shelton & Mackie (1971)
	<i>Homarus gammarus</i> (lobster)	Attracted to mixtures of amino acids, tertiary amines, nucleotides, nucleosides, and organic acids.	Mackie & Shelton (1972)
	<i>Homarus americanus</i> (lobster)	Mixtures of certain amino acids more attractive than pure extracts.	McLeese (1970a)
		Attracted to and ingested kerosene-soaked material; the cyclic and branched saturated hydrocarbons proved stimulatory.	Boylan <i>et al.</i> (1971)
Mollusks		Did not avoid bleached draft mill effluent at low concentrations.	McLeese (1970b)
		No response to "Putrid Cod" extract.	McLeese (1969)
	<i>Nassarius obsoletus</i> (mud snail)	Glyco proteins and proteins from human plasma and oyster fluid induced a strong feeding response.	Gurin & Carr (1971)
	<i>Urosalpinx cinerea</i> (oyster drill)	Solutions of glycine and lactic acid possessed marked stimulatory activity.	Carr (1967)
		Attracted by metabolites present in the excretions of its prey. Ammonium ion may be the initial attractant.	Blake (1960, 1962)
Crustaceans	<i>Lepas anatifera</i> (goose neck barnacle)	Positive response to solutions of amino acids plus organic and inorganic cations applied to mouth and cirri.	Crisp (1967)
Annelids	<i>Diopatra cuprea</i> (tube-dwelling polychaete)	Feeding response triggered by 6 unrelated amino acids, several sugars, some proteins, urea, and vegetable and mineral oil emulsions; repelled by volatile organic acids, ethyl alcohol, aged polychaete blood.	Mangum and Cox (1971)
Echinoderms	<i>Asterias rubens</i> (sea star)	Strongly repelled by bacteriological Peptone L37, L _x flutamic acid, mixtures of 10 common amino acids, and homogenates of <i>Mytilus edulis</i> flesh.	Castilla (1972)

concentrations of oxygen and high mixing rates at possible dump sites. Wrapping would further reduce these rates.

If oxygen concentrations of bottom water were to decline due to increased consumption over a wide area, an estimate can be made of the level at which changes in fauna would take place. Rhoads and Morse (1970) collected existing quantitative data on the distribution of benthic animals in oxygen-deficient marine basins. They identified a marked decline in numbers of species below 1-2

mg/l O₂. Species with heavy calcareous shells (mollusks and echinoderms) were not found where O₂ fell below 1.0 ml/l. A low diversity assemblage of small soft-bodied forms occurred where O₂ was between 0.3 and 1.0 ml/l. These included nematodes, polychaetes, holothurians, protobranch bivalves, and in some areas stomatopod and galatheid shrimp.

Of the three type-areas discussed in chapter II probably only the basins of the Gulf of Maine need to be considered in regard to oxygen depletion. An

estimate could be made of this depletion by using minimal initial oxygen content, minimal vertical diffusion rates, maximal oxygen consumption rates and maximal areas of waste coverage. Levels of oxygen under 2 ml/l could be considered as potentially harmful.

Anoxic conditions within the waste deposit would exclude non-tolerant infauna. It is not known whether these are deep sea parallels to the polychaetes that colonized the waste in the laboratory. Polychaetes and bivalves in anoxic sediments inshore usually occupy tubes or burrows through which oxygenated water is circulated. Characteristic deep sea species are detritus-feeders moving freely through the surface sediment. Young *et al.* (1971) described a silt-clay bottom in Cape Cod Bay which may be somewhat like the bottoms of the type-disposal areas. The area was dominated by a deposit-feeding holothurian whose activities resulted in unusually deep oxygen penetration of the sediment (7-9 cm). Infauna in such an area would not be preadapted to anoxic conditions.

Recent studies with shrimp (Haefner, 1971) and amphipods (Cook and Bond, 1965) have demonstrated an ability to sense oxygen. If this ability is widespread, it would allow animals to avoid deoxygenated areas. The typical elongated trough used for choice experiments induces crabs and lobsters to "blunder" into environments that may have been avoided in nature. More sensitive approaches are necessary to establish the behavior of animals in gradients of oxygen, H₂S and dissolved organic materials.

Fungal digestion of wood and paper may be inhibited by lack of oxygen near the waste surface. Kohlmeyer (1969) reported an absence of fungi in wood in a deep sea area with 0.3 ml/l oxygen and in wood buried in sediment.

Hydrogen Sulfide

Hydrogen sulfide produced within the waste deposit inhibits colonization by non-tolerant infauna as the lack of oxygen does.

Fouling was reduced in experimental tanks where relatively low flow allowed H₂S build up in overlying waters. It is not known whether this was due to inhibition of larval setting in response to water quality or to mortality following setting. In an actual waste deposit, fouling might develop on eleva-

tions but be absent in depressions where dispersion of H₂S would be slower.

H₂S will most likely appear in overlying waters at subtoxic concentrations (less than 1 ppm) which could have a repellent effect (Ishio, 1965). Laboratory studies on the effects of low concentrations of H₂S on the behavior of marine animals could help to explain the movements of animals over anoxic sediments in estuaries and marshes, as well as over deposits of sewage sludge and solid waste.

Food and Degradation Products

Fresh food will be present in newly deposited waste. Dayton and Hessler (1972) have described the attraction of fish, swimming decapods, octopods, large amphipods, brittle stars, sea cucumbers, polychaetes, and crabs to fresh bait placed on the deep sea floor. Scavengers assemble rapidly even in seemingly sterile areas. Current-borne sensory clues were indicated. Such scavengers would be attracted to newly emplaced waste bales. The lysionassid amphipods and hag fish are particularly aggressive and can be expected to enter perforations and holes in wrapping and to mechanically disturb unwrapped waste surfaces. J. McN. Sieburth (pers. comm.) has deployed "lunches" in double containers with 5 mm holes at 5300 meters depth in the northwest Atlantic. He found complete removal of all food by 70 days.

The mixture of substances resulting from anaerobic degradation of waste had no measurable attraction to crustaceans. A review of the literature suggests that "fresh" animal products are generally attractive to predators and scavengers while some degradation products are rejected. This could result in a loss of attraction of the waste deposit over time, possibly in as soon as a few months. Field studies on the attraction of scavengers to waste should be relatively straightforward and yield useful information about scavenger populations and their behavior.

Fouling

Both wrapped and unwrapped solid waste will provide hard surfaces on which fouling organisms could set. The coverage by fouling organisms at all sites will be less than in inshore waters. Ayers (1951) showed that the average rate of accumulation of fouling organisms near the bottom off south-

ern New England decreased from 0.5-0.05 lbs wet wt/mo/ft² along the coast to 0.01 on the central shelf. Depalma (1968) found that the rate of fouling off Florida diminished toward the bottom and in a seaward direction. No fouling occurred below the mixed layer except for trace amounts of "tube worms" and hydroids very close to the bottom. Turner (1963) also found an absence of fouling in deep waters off Bermuda. These results indicate that heavy fouling leading to containment or anchoring of waste will not occur even if eluates are not inhibiting.

Attack by boring shipworms (teredinids) is possible, however. Muraoka (1969, 1971) reports on the biodeterioration of test panels at various depths. He reported attack by *Xylophaga washingtona* of wood placed immediately over the bottom at up to 5640 foot depths. Plastics were attacked where they were in contact with wood.

It is not known whether teredinids would receive the proper chemical clues from compressed paper to initiate setting and boring. Previous colonization by "soft rot" fungus may be a prerequisite for attack. If this is so, the presence of oxygen at the deposit would be important because these fungi are strict aerobes. Muraoka (1969) reported that borers attacked manila rope but not disintegrating cotton rope.

Field studies will be the most rapid way to determine rates and types of fouling of waste at various ocean locations. Pearce (1971) has reported on the colonization of a bale of compacted domestic waste submerged for three months at 200 meters depth off the Virgin Islands. He found no encrusting organisms on the bale, anchoring chain, or weight, and only a relatively small population of loosely attached or motile organisms on the surface of the bale.

Cellulose

A recent report on the effects of overboard discharge of wastes (Oceanographer of the Navy, 1971) reviewed the fate of fabricated cellulose in the ocean and concluded that the rate of degradation is unknown but very slow. Deep sea photographs have revealed well preserved newspapers and other paper products. Manheim, Meade and Bond (1970) found fresh-appearing, unpitted cellulose fibers in the open ocean. The rate at which

cellulose is degraded will determine the longevity of waste deposits.

The presence of large amounts of paper fragments and cellulose fibers on the sea floor may cause special problems. Paper eroded from bales tends to form a low density slurry which is easily moved by currents and will not support most animals. Dean (1970) reported that only one polychaete was able to successfully colonize wood deposits in a Maine estuary because of their unstable nature. Pearce (1971) reported that deposits of lightweight residues from sewage sludge were transported across the bottom of New York Bight. The passage of such material was detected by reduced diversity and standing crop of the benthos and by debris incorporated into polychaete tubes.

Large quantities of cellulose fibers can be assimilated by benthic systems, however. Pearson (1970) made a careful study of pulp fiber disposal in a Scottish sea lock and found no changes in the benthic community which would be ascribed to the fiber.

Laboratory experiments are needed on the degradation rates of cellulose by benthic animals and by microbes with and without added nutrients. Field studies are necessary to establish the mobility of particles and the rates of entrapment and burial by animals and by sedimentation. Bruun and Wolff (1961) comment on the common occurrence of tree trunks, branches, twigs and other plant materials on the deep sea floor. Examination of the rate of delivery and "standing crop" of plant remains in various parts of the sea would help to understand the fate of cellulose from waste.

Bacteria

Visible bacterial films were characteristic of test waste deposits. These were eaten by at least three polychaete species. It has been hypothesized that bacteria form the basis of deep sea benthic food webs with the bacteria feeding on organic matter not directly digestible by animals (Zobell, 1954; Bruun, 1957). Jannasch (pers. comm.) has made an alternative suggestion that in the deep sea bacterial activity may be high only in the guts of animals.

Experiments have shown that bacteria are acceptable or necessary as food for various groups including: *Nereis*-polychaete (Zhukova, 1963), ciliates (Fenchel, 1969), nematodes (Tietjen *et al.*, 1970), and foraminifera (Muller and Lee, 1969).

The major part of the energy from a massive deposit of solid waste may eventually enter the food web as bacterial biomass. These include both heterotrophic forms utilizing dissolved organic matter and sulfide oxidizers. This form of energy transfer will be relatively slow and constant, a desirable effect if the view is held that the deep sea eco-

system is sensitive to perturbation. Bacterial films may also be important in wrapped waste. If current velocities are low (less than 1 cm/sec) bacterial films can form around the perforations in plastic wrapping material and even spread over their surface.

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MANUSCRIPT CHANGES

Page	Column	Paragraph	Line	Change
7	2	-	3-17	single paragraph
8	2	3	4	prove should be carry out
14	caption, figure III-3			part should be port
26	2	2	16-17	strike out repeated sentence
33	2	1	6	COD should be chemical oxidation
44	2	3	8	1.4 should be 0.7
47	2	2	9	(1971) should be (1972)

Add following references:

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