INLAND WATERS BRANCH

DEPARTMENT OF ENERGY, MINES AND RESOURCES

Pollution of Groundwater Due to Municipal Dumps

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Preface

This report was prepared under contract for the National Advisory Committee on Water Resources Research. It presents a review of the current literature on groundwater pollution due to municipal dumps.

Methods of solid waste collection and disposal *per se* lay outside the terms of reference of the contract and mention of them in the report is only incidental to the basic theme of groundwater pollution. Thus there is no discussion of such important topics as collection of refuse; day-to-day landfill operations; disposal methods such as grinding, compaction, composting and incineration; problems associated with construction of the completed landfill; and the final use of landfills. Despite this limitation, the report does provide a number of useful references to these topics, as is evident from a consideration of the two bibliographies that accompany it and as was perhaps inevitable, considering the intimate cause-and-effect relationship between pollution and disposal method.

The report provides good coverage of the following topics: groundwater pollution by solid wastes; significant research in this field; regulations; criteria for site selection; safeguards; and observation, detection and identification of pollutants. It also discusses groundwater pollution from other sources and the basic problems that commonly arise in the development of a rational approach to solid-waste disposal. Information on the contribution of immiscible fluids to the over-all solid waste disposal problem or on the significance of mixing, solution, dilution and chemical reaction was sought in rain. Precise knowledge of these factors will undoubtedly be of importance in the future solution of disposal problems.

It is hoped that this state-of-the-art survey will provide a solid working basis for administrators and engineers responsible for solid waste disposal and its regulation, as well as for scientists engaged in research on this problem and its environmental and ecological effects.

Introduction

The problem of disposing of solid wastes increases with population growth, particularly in metropolitan areas where, due to shortage of space, pressures develop to use landfill sites previously considered unsuitable.

Because of the economic benefits of short haulage distances on land reclamation there is great pressure to fill gravel pits and quarries. Filling of these sites, located in permeable or fractured rock, is quite likely to lead to pollution of ground water.

The old, open, burning dump is being replaced by the sanitary landfill; however, while the techniques involved in sanitary landfilling are designed to eliminate vectors and encourage a neat operation, they are not generally concerned with specific measures to prevent ground water pollution. There are techniques available for this purpose, but they are not generally used.

Much of the background information in this report has been abstracted by Hughes (1967) and Hughes et al (1968, 1970) from reports of the Joint Bureau of Solid Waste Management - University of Illinois Project.

Composition of Solid Wastes

Components in refuse, such as grass clippings, vegetables and ashes vary both regionally and seasonally; because of these variations and the difficulty of obtaining representative samples, analyses are of limited value. A typical breakdown of the physical and chemical composition of household refuse is given in Table 1 (Fungaroli et al 1968b, p. 11).

In recent years, the composition of domestic wastes has been changing because of the near elimination of returnable containers; this has resulted in a greater percentage of paper and paper products, glass bottles, aluminum cans, and plastic containers, and a considerable increase in the volume of waste generated. Legislation may reverse the trend in use of non-returnable containers for beverages at least. The Province of British Columbia has already restricted the use of non-returnable containers for beer and soft-drinks through the Litter Act, 1970. Industry and government are giving the possibilities of recycling many materials (primarily glass, paper and metals) more and more attention.

Conversion to oil and gas heating has reduced the ash content of domestic wastes.

TABLE 1

REFUSE COMPOSITION /1

Percent Composition of Refuse /2

Percent	
23.38	Corrugated paper boxes
9.40	Newspapers
6.80	Magazine paper
5.57	Brown paper
2.75	Mail
2.06	Paper food cartons
1.98	Tissue paper
0.76	Plastic coated paper
0.76	Wax cartons
2.29	Vegetable food wastes
1.53	Citrus rinds and seeds
2.29	Meat scraps, cooked
2.29	Fried fats
2.29	Wood
2.29	Ripe tree leaves
1.53	Flower garden plants
1.53	Lawn grass, green
1.53	Evergreens
0.76	Plastics
0.76	Rags
0.38	Leather goods
0.38	Rubber composition
0.76	Paints and oils
0.76	Vacuum cleaner catch
1.53	Dirt
6.86	Metals
7.73	Glass, ceramics, ash
9.05	Adjusted moisture
100.0	

Component	Cms. Pollutant/gm. dry refuse of wt. percent /3
Crude fiber	38.3%
Moisture content	18.2%
Ash	20.2%
Free carbon	0.57%
Nitrogen	
a) free	.02 mg/gram
b) organic	1.23 mg/gram
Water solubles:	
a) sodium	2.33 mg/gram
b) chloride	.97 mg/gram
c) sulfate	2.19 mg/gram
C.O.D.	42.29 mg/gram
Phosphate	.15 mg/gram
Hardness	10.12 mg/$CaCO_3$/gm.
Major Metals:	
Aluminum, Iron, Silicon	>5.00% (By spectrographic analysis) /4
Minor Metals:	
Calcium, Magnesium, Potassium	1/0-5.0% (By spectrographic analysis)

/1 Fungaroli et al. (1968, p. 11)
/2 Kaiser (1966) as presented in Fungaroli et al. (1968, p. 11)
/3 Preliminary results
/4 Of non-volatile portion

Processes and Products of Decomposition

Natural decomposition of buried organic refuse occurs through bacterial action by, and through, the action of other micro-organisms which utilize the refuse as food. Initially, decomposition is aerobic; that is, requiring the presence of oxygen. However, very soon after burial, when the oxygen supply is depleted, anaerobic processes predominate even in most "dry" landfills.

The components in the refuse decompose at various rates; sugar, starch, fats and proteins degrade more rapidly than fibrous cellulose materials such as wood and paper (Table 2).

Soluble materials in the refuse are released during decomposition and can be leached by percolating water - either ground water or water from precipitation; this leachate is high in dissolved solids and biological oxygen demand. Table 3 shows the percentage of the various components leached from refuse and from incinerator ash. Table 4 compares refuse leachate with other types of liquid wastes and U.S. Public Health Service standards.

Refuse leachate may contain unacceptable concentrations of almost all substances listed by the U.S. Public Health Service, and is comparable with food processing plant wastes in organic content and with chemical plant wastes in inorganic content.

A high concentration of refuse leachate in ground water makes it unfit for industrial or domestic use. Refuse leachate can also pollute surface water and, in addition, refuse disposal in open water may initiate the production of hydrogen sulphide and cause atmospheric pollution as well.

Gas is produced by decomposition of refuse, and is released to the surrounding ground and ground water and through landfill cover to the atmosphere. Carbon dioxide and methane are the most important of the gasses produced. Carbon dioxide increases the hardness and the acidity of the water which, in turn, adds to the solution and leaching of soluble constituents in the refuse. Methane forms a flammable mixture in air.

Attenuation and Migration of Dissolved Solids in the Subsurface

Refuse leachate in the sub-surface travels in the same direction as ground water, though at a slower rate. In a homogeneous isotropic environment, water moves vertically downward to the top of the zone of saturation and then in the direction of the potential gradient. The principles governing this movement were discussed by Hubbert (1940), Toth (1962), Meyboom (1966), Meyboom et al. (1966) and Freeze and Witherspoon (1966, 1967, 1968), and the effect on the movement of contaminants by Geraghty (1962).

TABLE 2

PROCESS OF DECOMPOSITION OF HOUSE REFUSE

HOUSE REFUSE

ORGANIC MATERIALS

MATERIALS CONTAINING CELLULOSE

Paper, Rags, Fruit Skin, etc.

ALPHA (Pure) CELLULOSE

The bacterial enzyme cellulose adds on the elements of water transforming the cellulose into the disaccharide (sugar) cellobiose.

By the bacterial enzyme, cellobiose, a further molecule of water is added to produce glucose.

Glucose is decomposed in one of two ways:

1. *Oxidation by aerobic bacteria into carbon dioxide gas and water with the liberation of heat (674 calories).*

   OR

2. *Anaerobic lactic acid bacteria will rearrange the glucose molecule into the molecule of lactic acid.*

Lactic acid is reduced to acetic acid, carbon dioxide and water.

Finally acetic acid is oxidised to carbon dioxide and water.

COMPLEX CELLULOSES (Hemicellulose and Lignocellulose).

Are reduced in a similar manner to alpha cellulose but, in addition to carbon dioxide gas, the gases methane and hydrogen are evolved.

PECTIN

Two actions are possible in the decomposition of pectin:

1. *The aerobic organism pectinobacter amilophilum can produce carbon dioxide and hydrogen gases with small portions of formic acid and alcohol;*

   AND

2. *The anaerobic granulobacter pectinovorum can yield butyric acid and alcohol with small amounts of carbon dioxide and hydrogen.*

FOODSTUFFS

1. *Of Animal Origin - Examples: Bacon, Beef, Fish*
2. *Of Plant Origin - Examples: Apples, Beans, Cabbage*

PROTEIN - ALBUMEN

Consists of Complex Nitrogenous Compounds in form of Amino-Acids

LEUCINE

Aerobic bacteria, proteolytic enzymes and oxygen act on this amino-acid, which is split up into carbon dioxide gas, water and ammonia gas. Considerable heat is given out (755 calories) during this process.

GLYCOCOLL

Is decomposed by aerobic bacteria much in the same way as leucine and into similar gases and water. Again heat is liberated (152 calories).

SULPHUR COMPOUNDS

Sulphur compounds are frequently present in protein. Bacteria and their enzymes reduce sulphur compounds first to sulphuretted hydrogen gas, then secondly to sulphuric acid or to sulphur and water.

CARBOHYDRATES

Sugar, Starch etc.

Aerobic bacteria and bacterial enzyme -- diastase -- change the carbohydrate into the gum, dextrin, and glucose.

Glucose is decomposed in one of two ways:

1. *Oxidation by aerobic bacteria into carbon dioxide gas and water, with the liberation of heat,*

   OR

2. *Anaerobic lactic acid bacteria will rearrange the glucose molecule into the molecule of lactic acid. Lactic acid is reduced to acetic acid, carbon dioxide, and water. Finally acetic acid is oxidised to carbon dioxide and water.*

FATS

Bacterial action through the bacterial enzyme, lipase, splits up the fat into fatty acids and glycerol

FATTY ACIDS

Generally are oxidised into carbon dioxide gas and methane gas by a biological oxidation involving the addition of water. An alternative method of reduction, by the enzyme lipase, produces alcohols and thence hydrogen gas.

GLYCEROL (glycerine)

Is first oxidised by B.xylinum to dihydroxyacetone, water being split off.

Dihydroxyacetone is changed to one of three forms:

1. *By the loss of a molecule of water methyl glyoxal is formed;*

   OR

2. *A rearrangement of the molecule produces lactic acid;*

   OR

3. *The dihydroxyacetone is split up into ethyl alcohol and carbon dioxide. The product of the reduction of dihydroxyacetone, whether 1, 2 or 3 is oxidised into acetic acid and carbon dioxide. Acetic acid is broken down into carbon dioxide and water or into carbon dioxide and methane.*

MINERAL SALTS

Exist in the foodstuffs in very small quantities only. Have a value as manurial constituents.

MOISTURE

Is essential to all processes of decomposition. In practically every one of the final steps of reduction of foodstuffs some water is released and in many of the earlier processes also. The surplus water helps to start the reduction of cellulose matter, later being again released.

INORGANIC MATERIALS

Not subject to change -- with the exception of metals such as iron which unite with oxygen, form oxides and gradually rust away -- but cause the body of the tip to be uneven and heterogeneous in character, influence the efficiency of the bacterial action and tend to lengthen the period taken to stabilise the tip and render the organic refuse inert.

TABLE 3

Percentages of Materials Leached from Refuse and Ash
(based on weight of refuse as received)

Materials leached	Percent leached 1†	2†	3†	4†	5†	6†
Permanganate value						
30 min.	0.039					
4 hrs.	0.060	0.037				
Chloride	0.105	0.127		0.11	0.087	
Ammoniacal nitrogen	0.055	0.037		0.036		
Biologic oxygen demand	0.515	0.249		1.27		
Organic carbon	0.285	0.163				
Sulfate	0.130	0.084 (as SO_4)		0.011	0.22	0.30
Sulfide	0.011					
Albuminoid nitrogen	0.005					
Alkalinity (as $CaCO_3$)				0.39	0.042	
Calcium				0.08	0.021	2.57
Magnesium				0.015	0.014	0.24
Sodium			0.260	0.075	0.078	0.29
Potassium			0.135	0.09	0.049	0.38
Total Iron				0.01		
Inorganic phosphate				0.0007		
Nitrate					0.0025	
Organic nitrogen	0.0075	0.0072		0.016		

† Source of data and conditions of leaching:

1. Ministry of Housing and Local Government (Gt. Brit.), 1961, p. 117. Analyses of leachate from domestic refuse deposited in standing water.

2. Ministry of Housing and Local Government (Gt. Brit.), 1961, p. 75. Analyses of leachate from domestic refuse deposited in unsaturated environment and leached only by natural precipitation.

3. Montgomery and Pomeroy, 1949, pp. 4 and 19. Refuse from Long Beach, California. Material leached in laboratory before and after ignition.

4. Engineering-Science, Inc., 1961, p. 39. Estimate based on data reported in "Final Report on the Investigation of Leaching of a Sanitary Landfill", (University of Southern California, Los Angeles, Sanitary Engineering Research Laboratory, 1954). Domestic refuse in Riverside, California, leached by water in a test bin.

5. Engineering-Science, Inc., 1961, p. 73. Based on data reported in "Investigation of Leaching of Ash Dumps", (University of Southern California, Los Angeles, Sanitary Engineering Research Laboratory, 1952). Leaching of California incinerator ash in a test bin by water.

6. Engineering-Science, Inc., 1961, p. 73. Based on data reported in "Investigation of Leaching of Ash Dumps", (University of Southern California, Los Angeles, Sanitary Engineering Research Laboratory, 1952). Leaching of Southern California incinerator ash in a test bin by acid.

TABLE 4

Comparison of Various Wastes with U.S. Public Health Service Standards
(in parts per million)

	U.S. Public Health Service Standards /2		Refuse Leachate			Sewerage /8		Slaughter house	Chem. plant
	Group I /3,4	Group II /5,6	1-3 yrs. old landfill /7	6 yrs. old landfill	17 yrs. old landfill	Influent	Effluent	wastes /9	effluent /10
Alkyl Benzene Sulfonage	0.05			0.72	0.30				
Arsenic	0.01	0.05	4.31	<0.10	4.6				
Chloride	250.		1697.	1330.	135.			320.	1070.
Copper	1.		0.05	<0.05	<0.05	0.450	0.032		2.1
Carbon Chloroform Extract	0.2								
Cyanide	0.01	0.2	0.024	<0.005	0.02		0.051		
Fluoride		3.4		2.	0.31				800.
Iron	0.3		5500.	6.3	0.6	2.600	0.038		51.
Manganese	0.05		1.66	0.06	0.06				0.48
Nitrate	45.		1.70	0.70	1.60				864.
Phenols	0.001								
Sulfate	250.		680.	2.	2.			370.	8120.
Total dissolved solids	500.		19144.	6794.	1198.			2690.	16090.
Zinc	5.			0.13	<0.10	0.638	0.366		
Barium		1.	8.5	0.80	0.30				
Cadmium		0.01	<0.05	<0.05	<0.05	0.	0.		
Chromium (Cr^{+6})		0.05	0.20	0.15	<0.05	0.	0.		
Lead		0.05		0.50	0.50	0.138	0.138		
Selenium		0.01	2.7	<0.10	<0.10				
Silver		0.05	<0.1	<0.1	<0.1				
Ammonium						19.	16.		198.
Alkalinity (as $CaCO_3$)			3255.	4159.	1011.			440.	760.
Hardness (as $CaCO_3$)			7830.	2200.	540.				0.
Phosphate			6.	1.20	8.90			66.	74.
Titanium									0.97
Aluminum			2.20	0.10	0.90				6.4
Sodium			900.	810.	74.				6190.
Hexane solubles			350.	18.	7.	22.4	11.		
Biological Oxygen Demand /11			54610.	14080.	225.	104.	17.	3700.	
Chemical Oxygen Demand			39680.	8000.	40.	240.	70.	8620.	
pH				6.3	7.0	7.2	7.4	8.1	6.2

/1 Modified from Hughes et al. (1970).
/2 U.S. Department of Health, Education and Welfare (1962).
/3 Nitrates exceeding 45 ppm. dangerous for infants.
/4 Should not be used if more suitable supplies available.
/5 Higher concentrations should be rejected.
/6 Fluoride is temperature dependent.
/7 Probably represents leachate from compaction and infiltration.
/8 Data provided by Metropolitan Sanitary District of Greater Chicago.
/9 Data from the files of the Illinois Department of Public Health.
/10 Rare earth and thorium production (Butler 1965, p. 63).
/11 20-day biological oxygen demand for leachate. Others are 5-day biological oxygen demand values.

As refuse leachate migrates through the ground, it is attenuated by ion exchange, dilution and dispersion. Fine textured materials, such as silts and clays, are particularly effective in removing dissolved solids from refuse leachate. This is because their lithology and large surface area favour ion exchange. Because fine textured materials have low permeability, only low rates of leachate movement are possible. Time is therefore available for continued bacterial action in, or near, the disposal site to degrade the leachate. Sands and gravels are less effective in ion exchanges and permit more rapid rates of travel. Dilution and dispersion are more important factors in leachate purification in these types of deposits. Fractured rocks are relatively ineffective in purifying leachate because flow is through channels, and contaminants may travel considerable distances with relatively little attenuation.

McKee and Wolf (1963, p.20) point out that low travel velocities and diffusion rates in ground water reservoirs can produce serious problems if contamination occurs. *Contamination may not be noticed for years or decades and, consequently, no complaints are registered. Even after contamination is discovered, the damage cannot be repaired merely by stopping the source of contamination.* Purification may require a longer time than the contamination.

Pollution of Ground Water

There are a number of cases on record of leachate from landfills migrating to pollute the ground water. Lang and Bruns (1940, p.8), Rössler (1951), Schlinker (1956) and Lang (1932) report instances of ground water contamination from solid waste disposal sites in Germany. Instances of pollution of water wells by landfills have also been reported in Illinois (Walker, 1969, pp.38-39). Considering the number of solid waste disposal sites in existence, there are relatively few instances of well pollution from this source described in the literature. This is partly because the inorganic contaminants which migrate farthest in the sub-surface must be present in relatively high concentration before they can be tasted, partly because funds are seldom available to investigate reported instances of "bad water", and partly because natural processes appear to be quite effective in removing dissolved solids from refuse leachate.

The examples of ground water pollution, which have been described, occurred when refuse was disposed of in relatively coarse materials which allowed for little attenuation and for rapid movement of the leachate.

Significant Research

The major investigations of the production and movement of dissolved solids and gasses from solid waste disposal sites have been made in California and Great Britain. Other investigations have been carried out in New York, Illinois, Pennsylvania, South Dakota, West Virginia and Wisconsin. With the exception of the studies in California, Great Britain and New York, most of these investigations have been initiated within the last ten years.

A comprehensive bibliography on sanitary landfills has been compiled by Steiner and Kantz (1968) and the California State Department of Public Health (1970) has compiled an annotated bibliography for solid waste disposal and water quality. A series of more general bibliographies on refuse collection and disposal has been prepared by the U.S. Public Health Service, (Van Derwerker and Weaver, 1951; U.S. Dept. of Health, Education and Welfare, 1954; Weaver, 1963; Williams, 1958; Williams and Black, 1961; Black and Davis, 1963; Black et al. 1966; and the Bureau of Solid Waste Management periodically publishes a list of the more available literature).

The principal Canadian investigators are H.M. Hughes and R.N. Farvolden. A report concerning refuse disposal in Toronto has been written by J.F. MacLaren Ltd.

Investigations in California

The University of Southern California (1952) published the results of an investigation of leaching in incinerator ash dumps. The quantity, quality, and ion exchange characteristics of leachate, produced by water percolating through cylinders filled with ash, were determined in the laboratory and a field study was made at a well, installed in an existing ash dump, from which leachate was collected. The principal conclusions drawn from this study were:-

1. incinerator ash forms a leachate high in dissolved solids;
2. rainfall will likely infiltrate incinerator ash dumps and produce a leachate.

The University of Southern California also carried out a study of leaching in a sanitary landfill from 1952 to 1960 (University of Southern California, 1954, 1955, 1956, 1958, 1960). Sampling points were installed within and beneath a landfill, and the ground water in the vicinity of the landfill was collected and analyzed. Water was percolated through bins of refuse, and gas and temperature studies were conducted.

This work demonstrated that:-

1. leachate, high in dissolved solids and capable of polluting the ground water, will be produced if a landfill is in intermittent or continuous contact with the ground water;
2. in Southern California, rainfall alone will not penetrate a 7.5-foot thick landfill;
3. decomposition in landfills is primarily anaerobic and carbon dioxide and methane will be produced.

Other follow-up studies of compaction, gas production, and temperature of refuse in drums or in specially constructed cells have been made in the same area (Merz, 1964; Merz and Stone, 1963, 1964, 1965 and 1966).

A series of investigations has been carried out by Engineering Science Inc., for the California State Water Quality Control Board. The first of these (1961) reviewed the information available on the effect of refuse dumps on ground water quality, and included discussions of vertical and horizontal movement of leachate, decomposition processes, and gas production and movement. Additional studies by Engineering Science Inc.

(1963-1966) were primarily field studies concerned with the amount of gas produced, its migration through the materials around and beneath landfill sites, and the settlement of landfills. These studies showed that gas production from landfills was quite variable, but that it did increase with higher moisture content.

Current studies by Engineering Science Inc. (1969) are directed towards control of the production of landfill gasses, the compaction and stabilization of refuse, the design of efficient landfill sites, and the development of construction and use criteria, including the design of liners and gas venting facilities.

Investigations in Great Britain

In Great Britain, a comprehensive laboratory and field study (Ministry of Housing and Local Government, 1961) was made of the quantity and quality of refuse leachate produced under saturated and unsaturated conditions, both in the laboratory and in large field installations. Studies were also made of changes in this leachate as it moved through sand and gravel filters. This study demonstrated that, in Britain, leachate would be produced by natural precipitation infiltrating refuse and the dissolved solids in this leachate, particularly the organics, were substantially reduced with migration through sand and gravel filters.

Studies of methods of refuse disposal in open water without producing undesirable amounts of hydrogen sulphide have also been made in Britain. Some of these are described by Furness (1954, 1956).

Bevan (1967) gives a review of the science and practice of the controlled disposal of refuse in Britain, including specific case histories; these include discussions of leachate treatment facilities and the use of completed landfills.

Other Investigations

Several papers (McCormick, 1966; Sawinski, 1966; Andersen and Dornbush, 1967) were published on the investigation of a landfill in South Dakota. Bored sampling points were installed to observe leachate that had moved from a landfill, located in shallow sand above a clay deposit, of relatively low permeability.

Analysis of samples of ground water collected downhill from the disposal site showed there were fluctuations in dissolved solids content, related to variations in climate. Part of the leachate migrating from this landfill passed through a small surface pond where a significant drop in dissolved solids, particularly hardness and alkalinity, occurred.

Some of the earliest landfill investigations were carried out in New York (Carpenter and Setter, 1940; Eliassen, 1942a, 1942b. Existing fills of various ages were sampled to determine the composition of the refuse leachate and gasses produced, and studies were made to determine the effect of moisture and paper content on the rate of refuse decomposition.

These studies showed that the most rapid decomposition occurs when the moisture content of the refuse is between 40% and 80%, that increasing paper content slows decomposition, and that decomposition is not as rapid in salt water as it is in fresh water.

Some detailed studies on the composition of refuse leachate and gasses have been done at the University of West Virginia. These include descriptions of the chemical content of seepage water from simulated landfills (Qasim, 1965), acid and gas production from sanitary landfills (Lin, 1966), and micro-biological and chemical investigation of seepage from a sanitary landfill (Cook, 1966).

In Pennsylvania, studies are underway at the Drexel Institute of Technology (Fungaroli et al., 1968a, 1968b, 1968c) and at Pennsylvania State University (Lane and Parizek, 1968). At Drexel, a large laboratory lysimeter filled with refuse has been constructed. Water is added to the top of this lysimeter, and temperature, compaction and leachate quality are observed. Studies are also being made at field installations. At Pennsylvania State University, part of an operating landfill is being monitored.

In Illinois, a study, jointly funded by the Bureau of Solid Waste Management and the University of Illinois, of the hydrogeology of solid waste disposal sites is nearing completion (Hughes et al; 1968, 1970). In that study, water sampling points and piezometers were installed in and around five landfills containing refuse up to twenty years old. Data were gathered on the amount of precipitation infiltrating the landfills, the composition of leachate from refuse of various ages, and of leachate after it had migrated various distances through different types of earth materials. The report includes a section on site selection, design, and operation.

The most significant conclusions arrived at in this study are that:-

1. unsuitable hydrogeologic environments might be made acceptable by including protective measures in the site design;
2. in North-eastern Illinois, 40% to 50% of the annual 33 inches of precipitation will infiltrate the surface of a landfill to produce a leachate, unless protective measures are taken;
3. the concentration of dissolved solids in the ground water, associated with a landfill, shows large variations over short vertical and horizontal distances. Some variations can be attributed to the age of the refuse;
4. based on studies in Illinois, silt and clay tills, unfractured shales, and clays with permeabilities of the order of 10^{-7} cm/sec. or lower, should reduce the total dissolved solids content of leachate by 1 or 2 orders of magnitude in travelling a distance of five feet. Fine sands and silts will reduce the total dissolved solids in leachate by about one order of magnitude in travelling 500 feet, and coarser sands, gravels and fractured rocks will reduce the total dissolved solids content correspondingly. When applying these data to other areas, differences in the ground water gradient, the mineralogy of the materials through which the leachate moved, and the initial composition of the leachate itself, must be considered. These data should therefore, be used with some discretion;
5. precipitation will infiltrate through fissures in the refuse, before the refuse reaches field capacity.

Investigations similar to those in Illinois, though in different hydrogeologic environments, are nearing completion in Wisconsin (Kaufmann, 1969).

Disposal operations in the Toronto area have become quite sophisticated and work has been carried out on leachate collection and treatment, and on venting buildings constructed on landfills. A disposal site in Etobicoke has been converted into a ski and toboggan hill over 100 feet high. Information on the work in this area has not been published, but is available from the personnel involved. Interested readers are referred to Mr. John Heaman and Wesley Williamson of the Ontario Department of Energy and Resources Management, Queens Park, Toronto, Ontario.

Summary

The foregoing studies have revealed the following facts:-

1. a polluting leachate can be produced by refuse in contact with water. The water may be ground water or surface water from precipitation. In arid climates, such as California's, precipitation is not adequate to infiltrate and produce a leachate from buried refuse. Therefore, in California, refuse buried above the top of the zone of saturation will not endanger the ground water resources. In Britain, Illinois and Wisconsin, investigations have demonstrated that precipitation will infiltrate refuse to produce a leachate unless measures are taken to seal the completed surface of the landfill. Similar conditions are likely to be present in most of Canada.

2. according to studies in Illinois and in Britain, dissolved solids in refuse leachate travel relatively short distances, and are rapidly attenuated in fine textured soils with relatively low permeability, such as fine sand, silt and clay, but may travel great distances with little attenuation in fractured rocks or permeable sands and gravels.

3. gases, as well as dissolved solids, are produced by the decomposition of refuse. These gases are predominantly methane and carbon dioxide. Methane may create explosion problems and carbon dioxide may increase the hardness of the ground water. Lateral sub-surface migration of methane from landfills is likely to be a problem at sites where thick permeable deposits lie above the zone of saturation. At sites located in relatively impermeable deposits, or where the zone of saturation is near the surface, methane is likely to be a problem to construction on the landfill itself. Only minor quantities of hydrogen sulphide are produced from buried refuse. When refuse is disposed of in open water, however, this gas can become a serious problem.

4. the length of time required for refuse to stabilize and stop producing contaminants cannot be readily predicted. The process is dependent upon a number of factors, including the moisture available, temperature, materials present in the landfill, and probably upon conditions of burial and compaction. Some landfills stabilize in three years (Schneider, 1953, p. 84); others still produce methane after 30 years (Eliassen, 1947, p. 757).

5. the designing of protective measures for otherwise unsuitable sites appears feasible and is being studied in California and Illinois.

Regulations Related to the Protection of Ground and Surface Waters and Hydrogeologic Criteria Used in Site Selection

Regulations range from generalities, which simply require that the landfill does not pollute ground or surface waters, to those specifying that certain physical conditions exist at the site to prevent such pollution, before disposal of certain types of materials will be allowed. Requirements are often vague, or technically incorrect, and personnel and funds are often inadequate for proper supervision.

The most common physical requirement designed to protect ground water is to ensure that refuse be deposited a certain distance above the top of the zone of saturation or, above the highest recorded level of the zone of saturation. This regulation is based on the California investigations which showed that, in Southern California, ground water pollution would not occur if the refuse did not intersect the top of the zone of saturation. It has little validity in areas where precipitation alone can produce leachate, unless provisions are included requiring that the final fill surface be covered with a material which would prevent the infiltration of precipitation. Other regulations dealing with physical conditions at the site are concerned with the thickness of "soil" or "clay", which must be present between the base of the refuse and the nearest aquifer, or the "water table".

The regulations designed to protect ground water do not consider sufficiently the hydrogeologic factors which influence site suitability. These factors include the exchange capacity of the materials in the vicinity of the site, and their permeability, the direction of ground water movement, the position of, and distance to the top of the zone of saturation and to the water supplies which are to be protected, and the design of the site, including the composition and configuration of the final surface of the landfill.

Regulations designed to protect surface waters commonly prohibit disposal in areas subject to flooding or where leachate is likely to enter surface waters. The former requirement is probably valid in that it prevents the blocking of drainage ways and hence, possible erosion and the scattering of refuse during floods. It is not necessary to prohibit disposal of leachate in surface water, but regulations should specify the concentration of dissolved solids in leachate which would be allowed to enter the surface water. Dilution of wastes, such as sewage, in surface water is generally accepted and a similar attitude should be taken towards leachate from solid wastes.

Regulations considering only some of these factors are likely to discriminate against some sites which may be suitable. On the other hand, regulations which considered all of the pertinent hydrogeologic factors would be hopelessly complex. A more realistic alternative would be to require that the landfill operator design his operation to meet effluent standards, set by the regulatory agency, and to submit his design to the regulatory agency for approval, as practised in other types of waste disposal operations. A major disadvantage of such a procedure is that, for it to be effective, funds and trained personnel must be available to the regulatory agency for evaluation and supervision of various types of landfill designs.

Current regulations do not generally consider basic hydrogeologic principles, or the more recent research, and should be modified accordingly.

Safeguards, Observation, Detection and Identification

The natural environment is usually relied upon to prevent the production of leachate in landfills, the migration of leachate from landfills, or to attenuate the leachate to acceptable or harmless levels during migration before it reaches a water resource. In some cases, landfill sites have been lined with earth or compacted earth to contain the leachate. As yet, there has been no investigations of such liners to see if they are functioning properly; however, earth liners are effective in reservoirs and liquid waste disposal sites and should be effective in containing leachate in solid waste disposal sites. If precipitation or surface runoff is allowed to infiltrate a landfill which has been lined to contain leachate, and the liner is effective, the landfill will eventually fill with water. This water must leave the landfill over the top of the liner and if the liner extends above the surrounding ground surface, leachate springs will result. This excess leachate must be collected and treated on the site or handled in some other manner.

Landfill gasses are usually handled by venting the landfill to the atmosphere and often burning the gas at the vent. (Eliassen et al, 1957, p. 115; Engineering News Record, 1948, p. 86; Dunn, 1960, p. 68; Fernand Benoit of Benoit and Associates, Montréal, personal communication). There has been some investigation in California of various types of liners to contain gasses, and studies of venting methods are currently underway (Engineering Science Inc., 1969).

Very little data are available on the treatment of refuse leachate. In Britain (Ministry of Housing and Local Government, 1961) considerable reduction in dissolved solids, particularly organics, was accomplished by passing leachate through horizontal sand and gravel filters. Treatment by ballast filters and holding ponds was effective in Bristol, England (Bevan, 1967, p. 146) and in Pennsylvania (Hughes et al., 1970); simple natural aeration lagoons, with a flow-through time of about one or two weeks, decreased the iron and biological oxygen demand of leachate by approximately 90%. It appears that leachate treatment is manageable and practical, particularly in view of the relatively small quantities that are likely to be produced under normal conditions.

Monitoring wells are seldom included in a landfill design, although they would be relatively inexpensive to install and would serve a very useful purpose. Such wells would aid in evaluating the effectiveness of a particular landfill design, and would give an early indication if something was wrong with the design so that remedial measures could be taken. They would also protect the landfill owner against false claims that he is causing ground water pollution. The actual positioning of monitoring points should be in accord with the hydrogeology of the particular site. After base levels are established, sampling and tests for total dissolved solids and chloride content could take place on an annual or semi-annual basis.

Table 4 compares the composition of refuse leachate of various ages with that of other liquid wastes. There are no components in refuse leachate which would specifically distinguish it from all other types of contamination. However, refuse leachate does contain large amounts of chlorides, iron, dissolved solids, alkalinity, hardness and organic matter. In older landfills where ashes have been buried, the sulphate content of the leachate is usually high.

Although the engineering procedures described have not been tested in the design of solid waste disposal sites, they are fairly standard procedures and have been tested in other facilities. As there is increased pressure to use marginal sites in metropolitan areas, more consideration will be given to incorporating protective measures into landfill site design.

Ground Water Pollution from Other Sources

There are numerous instances of ground water pollution reported in the literature. However, they generally involve the disposal of large quantities of liquid wastes rather than the smaller quantities associated with leachate from refuse disposal.

Calvert (1932) describes an instance in which liquor from a garbage reduction plant migrated 500 feet from a holding lagoon to pollute a well approximately 80 feet deep. Pollution of surface waters by a landfill at Denver, Colorado was described by McDermott (1950); ground water pollution, caused by organic matter decomposing in a storage reservoir in Pasadena, California, is discussed by Ackerman and Lynde (1944). In Texas, instances of ground water pollution by cotton seed delinting acid waste (Fink, 1964), and oil field brines (Fink, 1965; Burnitt and Crouch, 1964; Crouch and Burnitt, 1965) were investigated. These, and other instances of ground water contamination, illustrate that dissolved solids will move with the ground water. It appears, however, that studies of the migration of leachate from landfills have advanced past the stage where studies of the migration of contaminants, not present in leachate, can be of more than marginal value in developing criteria for landfill site selection.

Oil Field Brine Pollution

Brine pollution deserves the attention of the industry and regulatory agencies in areas where there is potash mining or petroleum exploration. Most problems of brine contaminating ground water or surface water occur by slow seepage of the brine into the aquifer and subsequent discharge in surface water.

Waters produced vary widely in degree of mineralization and chemical character. Available data indicate that sodium and chloride ions commonly constitute between 70% and 90% of the total ion concentration in produced brines. The brines are generally low in concentrations of sulphate and bicarbonate, and dissolved solids content is between 30,000 and 150,000 ppm.

High relative humidity and high precipitation rates, often prevent brines placed in unlined earthen pits from evaporating. In most cases, the effective surface area of disposal ponds is too small for significant evaporation to occur.

The mechanics by which brines are lost by seepage from unlined earthen surface pits, and their subsequent movement in the sub-surface, are influenced by the chemical character of the brine, lithologic characteristics of the material in which the pits are constructed, evapotranspiration, and geologic and hydrologic characteristics of the formations underlying the pits.

After continuous operation in some geologic terrains, deposition of sediment and mineral precipitations may result in a substantial reduction of effective pore space of materials in the bottoms of the pits, and, as a consequence the pits will no longer accept large volumes of water. In such instances, new pits are generally constructed, although, in many cases, dynamite or bore holes are employed in the bottom of existing pits to "increase evaporation".

The rate and path of fluid seepage from an earthen surface pit constructed in sand or sandstone is determined to a great extent by the relative permeabilities of the beds underlying the pit. Although the downward path of the brine under the influence of gravity is essentially vertical, layers of shale or clay may temporarily impede movement through the zone of aeration, so that the contaminant may move laterally for comparatively long distances before reaching the ground water, and in some instances, may be discharged into surface drainageways before percolating to significant depths.

The movement of fluid contaminants in the saturated zones of ground water aquifers is determined by the same geohydrologic factors which control the movement of natural ground water. Investigations of ground water contamination have indicated that, in undisturbed parts of aquifers, ionic diffusion of oil-field brines in ground water is a relatively slow process. In water-table aquifers made up predominantly of sand and sandstone, brine contaminants move from their source in the direction of the hydraulic gradient in relatively little disbursement.

Sub-surface injection has become increasingly widespread in recent years, particularly in areas where secondary-recovery operations have been initiated or where widespread contamination has apparently resulted from surface disposal of brines. It is reported that there are in the order of 20,000 to 30,000 injection wells in Texas.

Whether the objective of the injection operation is to increase hydrocarbon production or to dispose of produced brines, the important point essential to water-quality protection is that the injection well must be constructed so as to prevent escape of injected brines from the selected injection zones, and monitoring procedures should be built into the injection system to detect subsequent equipment failures or other problems which may develop.

Pollution Due to Pulp and Paper Processing

The pulping process known as NSSC (neutral sulphite semi-chemical) uses a mixture of sodium sulphite and sodium carbonate to cook wood chips. The liquid waste produced, containing dissolved organic material from the wood as well as the original inorganic chemicals, is normally sewered. This untreated waste could easily enter ground water systems because sewers are not necessarily impermeable.

Intensified anti-pollution legislation would force NSSC mills to dispose of the liquid waste in some other manner. The liquid wasted could be treated in a fluidized bed reactor, producing a salt cake of dry sodium carbonate and sodium sulphate. Complete conversion to the sulphate could be accomplished by adding elemental sulphur, making the product suitable for kraft mill use.

Basic Problems

The basic problems in the disposal of solid wastes are lack of co-ordination of various authorities and insufficient knowledge concerning possible safe waste disposal sites.

A recent report from California (California State Department of Public Health, 1970) on the problem of solid waste disposal reaches the following conclusion:-

"California's most urgent need concerning solid waste is an effective mechanism for co-ordinating state, local, and private responsibilities in managing these wastes in a manner consistent with optimum public health and environmental quality criteria. Meeting this need will require a carefully conceived, thoroughly planned and vigorously executed program based on *clearly defined authority and adequate resources for both state and local government participation*".

There has probably been more work done in the field of solid waste disposal in California than in any other area, and in our opinion, the preceding statement is valid for Canada as well as for California. Unless regulatory agencies are staffed with technically competent personnel and given sufficient funds and authority, regulation of landfills will be ineffective.

Another important requirement is that the understanding of the capabilities of the natural environment to attenuate contaminants, and of techniques and procedures which can be used in questionable environments to insure that safe disposal can take place, be improved. Some of the problems which should be investigated are: the effectiveness of various types of liners; mechanisms by which contaminants are removed from leachate by natural processes; effects of slope, materials and vegetation on infiltration into a landfill and methods of leachate treatment.

Present knowledge makes it possible to protect the environment by restricting disposal to those sites which it is believed are safe or can be made safe. Further research would disclose more sites which could be safely used.

Conclusions

Protection of ground water resources from pollution by solid waste disposal operations does not appear to present insurmountable technical problems.

There are numerous naturally protected hydrogeologic environments in which solid wastes could safely be disposed of, and there are a number of protective measures that could be applied to the environment in areas which are not naturally protected.

Most instances of pollution have been the result of disposal in obviously unsuitable sites. Future pollution could be avoided by more careful observation, stringent detection techniques, proper safeguards and stricter regulations.

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Respectfully submitted,

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Some Examples of Rules and Regulations
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APPENDIX B.

APPENDIX "B"

Rules and Regulations

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