OLD DOMINION UNIVERSITY RESEARCH FOUNDATION

DEPARTMENT OF CIVIL ENGINEERING
SCHOOL OF ENGINEERING
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA

# INTERPRETATION OF THE CHARACTERISTICS OF OCEAN-DUMPED SEWAGE SLUDGE RELATED TO REMOTE SENSING

(NASA-CR-158454) INTERPRETATION OF THE CHARACTERISTICS OF OCEAN-DUMPED SEWAGE SLUDGE RELATED TO REMOTE SENSING Final Report, 18 Jul. 1977 - 17 Feb. 1979 (Old Dominion Univ. Research Foundation) 94 p HC G3/43
N79-21522
Unclas
19479

*By*

Philip S. Pagoria

*and*

Chin Y. Kuo, Principal Investigator

Final Report - Part II
For the period July 18, 1977 - February 17, 1979

*Prepared for the*
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia

*Under*
Research Grant NSG 1441
Robert W. Johnson, Technical Monitor
Marine and Applications Technology Division

April 1979

MAY 1979
RECEIVED
NASA STI FACILITY
ACCESS DEPT.

DEPARTMENT OF CIVIL ENGINEERING
SCHOOL OF ENGINEERING
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA

# INTERPRETATION OF THE CHARACTERISTICS OF OCEAN-DUMPED SEWAGE SLUDGE RELATED TO REMOTE SENSING

*By*

Philip S. Pagoria

*and*

Chin Y. Kuo, Principal Investigator

Final Report - Part II
For the period July 18, 1977 - February 17, 1979

*Prepared for the*
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia  23665

*Under*
Research Grant NSG 1441
Robert W. Johnson, Technical Monitor
Marine and Applications Technology Division

*Submitted by the*
Old Dominion University Research Foundation
P. O. Box 6369
Norfolk, Virginia  23508

April 1979

## TABLE OF CONTENTS

## LIST OF TABLES

Table

(Continued)

# LIST OF TABLES (Continued)

# LIST OF TABLES (Concluded)

# LIST OF FIGURES

## LIST OF FIGURES (Concluded)

# INTERPRETATION OF THE CHARACTERISTICS OF OCEAN-DUMPED SEWAGE SLUDGE RELATED TO REMOTE SENSING

By

Philip S. Pagoria[1] and Chin Y. Kuo[2]

## SUMMARY

The purpose of this report was to define watewater sludge characteristics in general, and characteristics of wastewater sludges generated by the City of Philadelphia in particular, as they are related to interpretation of ocean disposal remote sensing experiments. Specific questions addressed included defining differences between primary and secondary sludges, comparing characteristics for east coast sludges receiving ocean disposal, determining the influence of the anaerobic digestion process on sludge characteristics, and reasoning whether or not remote sensing techniques should be able to differentiate between the various wastewater sludge types.

To accomplish these purposes the report is divided into a number of sections, including explanation of the types and sources of wastewater sludges, description of sludge treatment and disposal processes, examination of sludge generation and management for the City of Philadelphia, and definition of characteristics for typical east coast sludges undergoing ocean disposal.

It was found that specific differences do exist between the characteristics of primary and secondary wastewater sludges, especially with the nature and size distribution of the solids particles. However, the sludges from the City of Philadelphia monitored during remote sensing experiments were found to be mixtures of various sludge types and therefore were found to lose their distinguishing characteristics. In particular the anaerobic digestion process was found to exert the most significant influence on sludge characteristics for the City of Philadelphia. On comparison with characteristics

---

[1] Assistant Professor, Department of Civil Engineering, Old Dominion University, Norfolk, Virginia 23508.

[2] Associate Professor, Department of Civil Engineering, Old Dominion University, Norfolk, Virginia 23508.

of other east coast municipal wastewater sludges, the sludges generated by the City of Philadelphia were found to be quite typical and harbor no unique features.

# 1. INTRODUCTION

## 1.1. Statement of Problem

Many people have stated that disposal of generated residues, or sludges, is the most difficult part of the task of wastewater treatment (ref. 1). For example, in the United States the cost of sludge treatment and disposal has been estimated to account for 25 to 50 percent of the total cost of wastewater management, with the higher figure being more prevalent (ref. 2). The sludge produced by municipal wastewater treatment plants in the United States is disposed of in various ways. Approximately 15 percent is dumped in the ocean, 40 percent deposited in sanitary landfills, 20 percent used as an agricultural resource on land, 5 percent spread on land not in agricultural use, and 25 percent incinerated (ref. 3). Ocean disposal, although substantial for some highly populated coastal areas such as New York City, Philadelphia, and Los Angeles, is employed by comparatively few municipalities.

Circulation patterns, interaction of water movements with bottom topography, and biological processes control movements and fate of sludges discharged to coastal ocean waters (ref. 3). Considerable concern and controversy has arisen over potential adverse environmental side effects of ocean sludge disposal (ref. 4). Table 1 summarizes environmental behavior and possible environmental effects for typical constituents of municipal wastewater sludge.

Table 1. Summary of behavior and environmental effects in coastal ocean areas of significant constituents in sludge (ref. 3).

| Constituent | Environmental Behavior | Environmental Effect |
|---|---|---|
| Pathogens<br>Bacteria<br>Viruses | Associated with particles and surface films | Possible transfers to humans through ingestion (food or liquids) and body contact sports |
| Metals<br>Lead<br>Cadmium<br>Mercury | Dissolved and/or associated with particles | Concentration by organisms (e.g., shellfish). Possible transfers to humans through shellfish or other seafood |
| Polychlorinated biphenyls | Associated with particles | Concentration by organisms |
| Low-density solids | Easily eroded and transported by currents and wave action | Changed benthic community and abundance of organisms. Possible transport of pathogens and chemical constituents |
| Nutrients<br>Phosphate<br>Nitrogen compounds | Dissolved in waters, locally concentrated by marine phytoplankton | Increased productivity. Possible depletions of dissolved oxygen in near-bottom waters |

Because of the expressed concerns, the U. S. Congress enacted PL 92-532, the Marine Protection, Research, and Sanctuaries Act of 1972. This legislation had the direct consequence of placing the fate of ocean disposal of sludge in the hands of the Federal Government, specifically of the Environmental Protection Agency (EPA). Current EPA policy states that ocean dumping of wastewater sludge shall be ended by December 31, 1981 (ref. 5). However, examination of PL 92-532 makes it clear that the extent to which ocean disposal of sludge has actually been curtailed or abandoned was not mandated by Congress, but rather was left within the reasonable discretion of EPA. A recent national study undertaken by the National Research Council (ref. 3) concluded that the absolute prohibition of ocean disposal of sludge was not justified because such action assumes that in all instances other disposal options will be less harmful to the environment. Therefore, there exists a reasonable chance that controlled and monitored ocean disposal of sludge may be practiced beyond the 1981 deadline.

Up until this date, and possibly beyond if EPA reconsiders its position, there exists a need for techniques to monitor ocean disposal of sludge. On the west coast of the United States sludge is discharged from submerged outfalls which extend into deep submarine canyons. Because of their fixed positions, these sludge discharges are relatively easy to monitor with conventional oceanographic water quality techniques. On the east coast, however, ocean sludge disposal is primarily carried out by barging sludge offshore and releasing at the ocean surface. Because of the transportation involved and the mobility of the dumping vessels, it is difficult to adequately insure that all sludge is dumped in the designated disposal areas with the proper release techniques.

Remote sensing techniques, using sensor systems usually borne by aircraft or spacecraft, offer a potention solution for the problem of monitoring ocean sludge-dumping activities. Incident electromagnetic energy striking the ocean's surface can be transmitted, absorbed, reflected, emitted, or scattered. The particular combination of these interactions displayed by the ocean's surface results in a unique spectral signature analogous to a human fingerprint (ref. 6). Remote sensing techniques can utilize this relationship and modification of the spectral signature caused by sludge disposal to identify and measure environmental parameters, including some water quality parameters.

Laboratory experiments have examined the upwelled spectral signature for sewage sludge mixtures of varying concentration (ref. 7). Field remote sensing experiments involving operating east coast sludge disposal sites have also been carried out (refs. 8 to 10). One important conclusion of these experiments has been that differences in sludge characteristics among the various sewage sludge types, such as primary or secondary, which could account for differences in spectral response, must be explored and defined. In particular, a number of the laboratory and field studies mentioned above have centered around wastewater sludges generated by the City of Philadelphia. Therefore characteristics of these sludges require particular evaluation. The purpose of this report is to define sludge characteristics in general, and City of Philadelphia sludge characteristics in particular, as they relate to remote sensing response.

## 1.2. Specific Research Questions

In order to meet the stated purpose of this report, the following specific questions are addressed:

(1) What are the specific differences between primary and secondary sludges resulting from municipal wastewater treatment?

(2) Is the sewage sludge taken for ocean disposal from the City of Philadelphia comparable to or typical of east coast municipal sludges, or are the characteristics of the Philadelphia sludges unique?

(3) Is the major influence on water quality following ocean disposal the sludge type (primary or secondary) or the sludge processing history, especially if it includes anaerobic digestion? (A related question is "How important an influence is anaerobic digestion on sludge characteristics?")

(4) Based on sludge characteristics and water quality interactions with seawater, should remote sensing techniques differentiate between different sludge types such as primary, secondary, raw, or anaerobically digested?

A related subject area concerns the effect of sewage sludge-seawater interaction on sludge particle size. This question is not discussed independently, but rather is addressed during the description of particle size as a sludge characteristic.

## 1.3. Report Organization

To accomplish the stated purpose of this report and answer questions just detailed, the report is divided into a number of sections. In section 2, typical wastewater treatment processes are briefly examined to indicate the types and sources of wastewater sludge along with general sludge properties. Then specific characteristics for primary and secondary sludges are reviewed in detail. In section 3 sludge treatment processes are outlined to define the influence of these operations on major sludge characteristics. Since the City of Philadelphia utilizes the anaerobic digestion process, specific attention is devoted to its description and effects on sludge properties.

City of Philadelphia municipal wastewater sludges, their sources, processing, and characteristics are covered in section 4. Emphasis is placed on those aspects which might influence interpretation of remote sensing data involving these particular sludges. To determine whether or not Philadelphia's sludges are typical of other east coast sludges, a survey of east coast municipalities practicing ocean sludge disposal was undertaken (see section 5). Finally, results of this survey and comparisons to Philadelphia's sludges are reported in section 6.

# 2. TYPES AND SOURCES OF WASTEWATER SLUDGES

The characteristics of sludges generated by wastewater treatment processes are profoundly influenced by many factors, the most important of which is the generating process itself. Therefore, in order to gain an understanding of differences between various categories of sludge, it is necessary to briefly review wastewater treatment processes. The purpose of the following section is to examine typical wastewater treatment processes, identifying points of sludge generation, generation rates, and general sludge properties.

## 2.1. Typical Wastewater Treatment Processes

The majority of wastewater treatment processes remove soluble and colloidal impurities by first converting them to a solid form which can be more easily separated from the surrounding liquid. Thus, each process operating on this principle generates residual solids or sludge. Wastewater treatment processes are typically divided into three major categories based on the degree of pollutant removal that is attained: primary, secondary, or tertiary.

Table 2 details major unit treatment processes which are employed in various combinations to achieve primary, secondary, or tertiary treatment. In general, primary treatment refers to the use of physical unit processes to remove suspended solids. Secondary treatment usually involves use of a controlled biological population to achieve biodegradable organic pollutant reductions. Tertiary, or advanced wastewater treatment, applies specialized techniques to remove particular pollutants such as nitrogen forms, phosphorus, heavy metals, or refractory organic compounds.

Table 3 provides an indication of the relative frequency of application for major wastewater treatment processes. Present Federal law mandates secondary treatment, which normally follows primary treatment, and encourages increased land application of wastewater. Therefore, the percentage of systems using primary sedimentation only should drop to zero by 1983, while percentages for activated sludge secondary treatment and land application should significantly increase.

Table 2. Major wastewater treatment processes (ref. 13).

| Contaminant | Unit Process or Treatment System |
|---|---|
| Suspended Solids | Sedimentation |
| | Screening and comminution |
| | Filtration variations |
| | Flotation |
| | Chemical-polymer addition |
| | Coagulation/sedimentation |
| | Land treatment systems |
| Biodegradable organics | Activated-sludge variations |
| | Fixed-film: trickling filters |
| | Fixed-film: rotating biological contractors |
| | Lagoon variations |
| | Intermittent sand filtration |
| | Land treatment systems |
| | Physical-chemical systems |
| Pathogens | Chlorination |
| | Hypochlorination |
| | Ozonation |
| | Land treatment systems |
| Nutrients: | |
| Nitrogen | Suspended-growth nitrification and denitrification variations |
| | Fixed-film nitrification and denitrification variations |
| | Ammonia stripping |
| | Ion exchange |
| | Breakpoint chlorination |
| | Land treatment systems |
| Phosphorus | Metal-salt addition |
| | Lime coagulation/sedimentation |
| | Biological-chemical phosphorus removal |
| | Land treatment systems |
| Refractory organics | Carbon absorption |
| | Tertiary ozonation |
| | Land treatment systems |
| Heavy metals | Chemical precipitation |
| | Ion exchange |
| | Land treatment systems |
| Dissolved inorganic solids | Ion exchange |
| | Reverse osmosis |
| | Electrodialysis |

Table 3. Distribution of types of wastewater treatment processes (ref. 3):[a]

| Treatment Process | Percentage of Total Facilities Using Treatment Process |
|---|---|
| None | 11.6 |
| Primary sedimentation (alone) | 14.2 |
| Activated sludge | 20.3 |
| Trickling filter | 20.4 |
| Chemical precipitation | 5.0 |
| Secondary treatment (using processes other than trickling filters or activated sludge) | 2.4 |
| Advanced (tertiary) | 2.3 |
| Ponds or lagoons | 22.3 |
| Land disposal | 0.7 |

[a] Based on 1975 U. S. Environmental Protection Agency Data.

Before detailing sludge sources, it is necessary to examine a number of the treatment processes discussed in tables 2 and 3 in greater depth.

2.1.1. Primary sedimentation. - This process represents a technique whereby the velocity of a wastewater flow is reduced. This velocity reduction allows a fraction of the suspended solids to settle under the force of gravity, thus causing separation from the original wastewater. Velocity reduction is achieved by introducing wastewater into large circular or rectangular sedimentation basins with minimal agitation or mixing. Organic suspended solids removed by primary sedimentation consist mainly of proteins, fats, and some cellulose (ref. 11).

Most coarse materials, such as sticks, rags, and other large objects, found in municipal wastewater are removed prior to primary sedimentation by coarse screening operations. Similarly, dense inorganic solid particles such as sand and gravel are removed in grit chambers which precede primary sedimentation. The specific gravity of solid particles still suspended in waste water reaching the primary sedimentation process varies from less than 1.0 to nearly 1.2 (ref. 12). De-emulsified soap, oil, grease, and some fats tend to rise to the surface of primary sedimentation basins forming a scum layer.

The separated solids which accumulate during primary sedimentation are usually allowed to thicken by gravity compaction in the bottom of the basin. Removal to some type of solids processing and disposal facility then follows. The separated solids are termed primary sludge and generally have a solids content of 4 to 12 percent (96 to 88 percent water) (ref. 13).

2.1.2. Chemical coagulation and flocculation. - The degree of solids separation in primary treatment processes may be greatly increased by using chemical coagulants which encourage flocculation of solids particles. Through a series of complex reactions dependent on both properties of the chemical coagulant and solids particles, particle size growth is encouraged. Particle properties are altered so that individual particles aggregate together in larger masses or flocs, this aggregation being catalyzed by mixing energy which causes particle contact. The larger, heavier flocs which result are then more easily removed by gravitational settling. Removal of both suspended and colloidal wastewater solids can be increased in this manner.

Chemical coagulants used to bring about flocculation include aluminum sulfate, lime, ferric chloride, ferrous sulfate, sodium aluminate, and synthetic organic polyelectrolytes. Since these compounds or their solid reaction products settle with the solids particles originally in the wastewater, their use can significantly influence the properties of primary sludge.

2.1.3. Secondary Treatment Processes. - Most commonly employed processes for secondary wastewater treatment involve controlled microbiological population growth. Countless bacteria play a vital role in a typical biological wastewater treatment system. These bacteria convert soluble and colloidal organic compounds into settleable bacterial mass and oxidized inorganic compounds.

In theory, biological wastewater treatment systems essentially duplicate processes which occur during natural stream purification. The major difference is that control of environmental conditions in wastewater systems allows intensification of the microbiological populations and shortens required reaction times. The majority of biological wastewater treatment processes follow aerobic (oxygen based) metabolic pathways. Therefore, systems are designed to supply supplemental oxygen to the biological processes in order to maintain aerobic conditions.

As indicated previously in table 3, the most common forms of secondary treatment systems in practice are trickling filter, activated sludge, and oxidation pond or lagoon processes. For large municipal installations, the activated sludge and trickling filter processes dominate. The major difference between these two processes relates to the location of the microbiological population and the method in which wastewater is brought into contact with it. In the activated sludge process the microorganisms are suspended in, and move with, the wastewater. Such an arrangement is referred to as a suspended-growth process (ref. 13). In the trickling filter process the microorganisms are attached or fixed to a rigid supporting medium. Wastewater is then passed over the medium to bring about contact with the microorganisms. Such an arrangement is referred to as an attached-growth process (ref. 13).

A biological treatment method similar to trickling filters is the rotating biological contactor process. Like trickling filters, the microbiological population is attached to a rigid supporting medium. The difference is that this medium is mounted on a rotating shaft which immerses a portion of the microorganism/media combination in wastewater. Therefore the microorganisms are passed through the wastewater instead of remaining stationary while the wastewater is circulated. The City of Philadelphia is using this biological process in combination with an existing activated sludge system at its Northeast Wastewater Treatment Plant. The combined biological treatment scheme has been named the "surfact" process.

Figure 1 illustrates a typical wastewater treatment flow scheme with some type of biological process for secondary treatment. Raw wastewater first passes through preliminary treatment steps consisting of coarse screening [typically 0.5- to 3-in. (1.3- to 7.6-cm) clear openings between bars] and grit removal. Preliminary treatment may also include pre-aeration or prechlorination steps if certain wastewater characteristics, such as a complete lack of dissolved oxygen or significant hydrogen sulfide concentrations, cause odor problems or adversely influence downstream biological processes.

From preliminary treatment wastewater passes to primary sedimentation basins where settleable solids are removed. Efficiently designed and operated basins are capable of removing 50 to 70 percent of the suspended solids

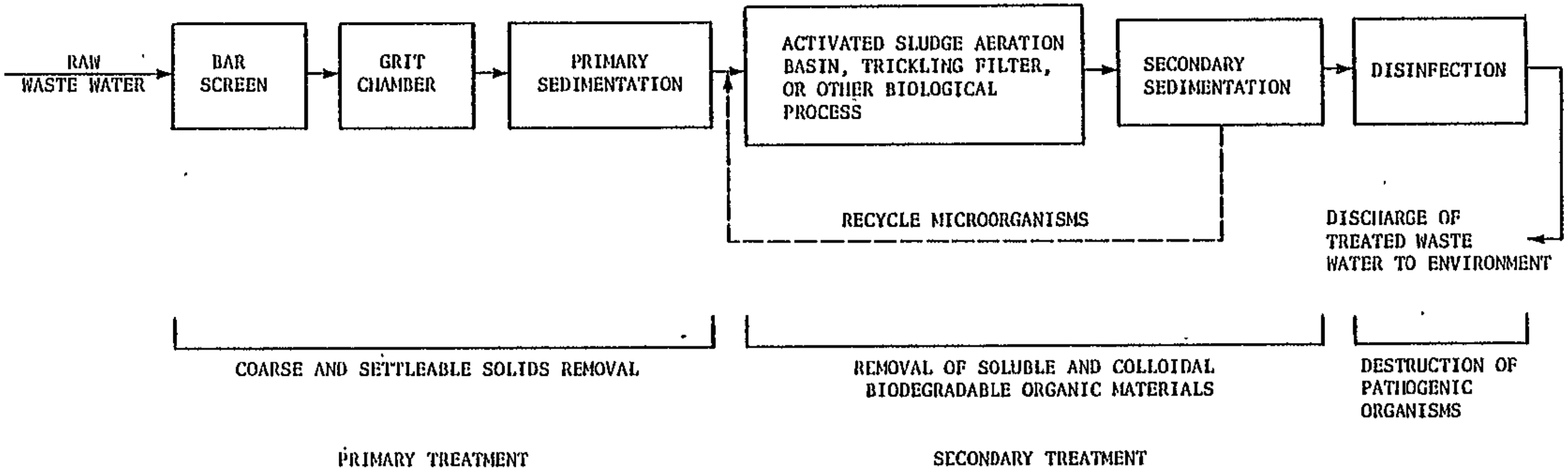

Figure 1. Typical secondary treatment system configuration.

(SS) and from 25 to 40 percent of the 5-day, 20°C biochemical oxygen demand (BOD) (ref. 13). Primary sedimentation effluent then proceeds to a biological reactor containing a population of microorganisms acclimated to the organic characteristics of the wastewater. The dashed line in figure 1 indicates that suspended-growth processes, such as the activated sludge process, must recycle microorganisms to maintain a large population in the reactor. The key point in understanding any biological wastewater treatment process, and most importantly characteristics of the resulting sludges, is that such processes represent a conversion step. Soluble and colloidal organic materials cannot be easily separated from wastewater unless they are converted to solid form. Such solids are then susceptible to gravity sedimentation to effect separation from the bulk liquid. Figure 2 illustrates this conversion and separation process.

Biodegradable soluble and colloidal organic materials are utilized by the varied microbial populations for two purposes:

(1) a portion of the organic material is oxidized to release chemically stored energy required for organism metabolism and synthesis, and (2) a larger portion is utilized as a source of carbon and other nutrients, providing the essential building blocks for the synthesis of additional microorganisms or microbial mass.

Of the total mass of biodegradable organic materials quantified as 5-day 20°C BOD entering a biological reactor, roughly 85 to 95 percent is utilized by the microbial populations (ref. 13). Of this amount removed from the waste water, approximately 30 to 40 percent is oxidized into stable end products including carbon dioxide, water, sulfates, and nitrates. The remaining 60 to 70 percent is synthesized into new microorganisms (ref. 14). Overall there is a net accumulation of synthesized microorganisms beyond the critical mass or population which is needed to sustain the biological system. It is this excess of microbial mass which must be wasted from the process and which represents biological or secondary sludge.

The critical step in any biological wastewater treatment process is the separation of synthesized microbial mass from the wastewater in which it is suspended and transported. If this separation cannot be efficiently achieved, the performance of the biological process, in terms of biodegradable organic

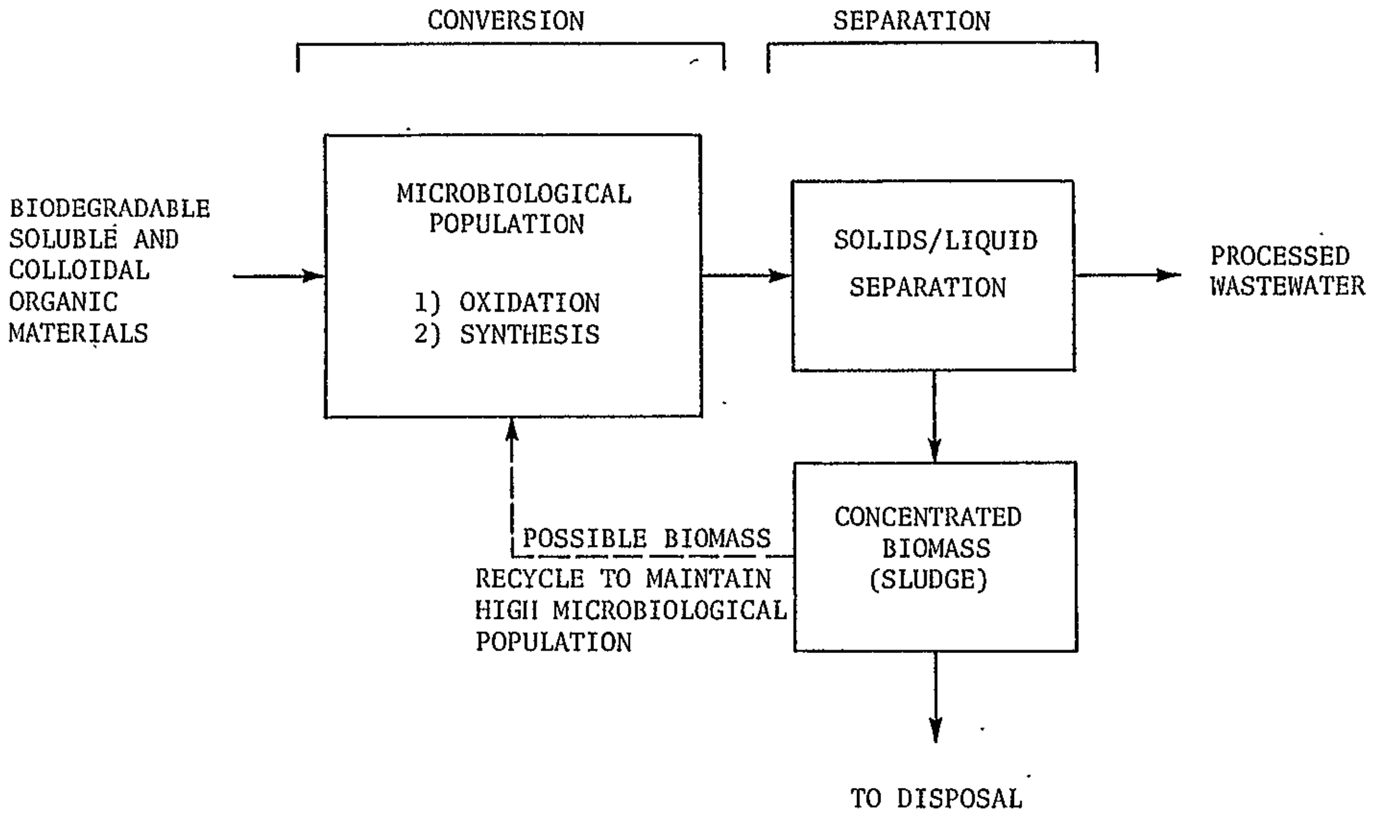

Figure 2. Fundamental steps in biological wastewater treatment.

removal, can be significantly lowered. This occurs because the synthesized microbial mass is just another form of biodegradable organic matter which is capable of exerting a significant biochemical oxygen demand.

Since microbial mass is composed of living microorganisms, numerous environmental conditions influence its physical condition or the species of microorganisms which dominate. Both factors affect the settling properties of the microbial suspended solids and determine whether solids-liquid separation will be effectively achieved. Adverse environmental conditions include fluctuations in availability of organic materials or wastewater flow rate, high or low pH conditions, presence of biologically toxic substances such as heavy metals or pesticides, and deficiencies in required nutrients such as nitrogen and phosphorus (ref. 15). Such conditions are commonplace, and process upsets of biological wastewater treatment systems exert a profound influence on the characteristics of biologically generated sludges.

## 2.2. Sludge Sources and Generation Rates

Having briefly reviewed typical wastewater treatment processes, it is now necessary to examine specific sludge generation and discharge points within these processes. In order to develop an understanding of the magnitude of the sludge processing and disposal task, it is also necessary to examine sludge generation rates. Review of both these areas will provide the background for an examination of sludge characteristics.

2.2.1. Points of sludge generation and release. - Since the major method of pollutant reduction in wastewater treatment is by removal in solid form, there are many points of solids generation and discharge. Figure 3 indicates the major residual solids, or sludge, generating unit processes in a typical activated sludge process wastewater treatment plant. Not indicated on the diagram are points of scum generation, since scum is usually processed and disposed of separately from sludge. However, it should be noted that scum is commonly skimmed from the surface of pre-aeration tanks, aerated grit chambers, primary sedimentation basins, and secondary sedimentation tanks.

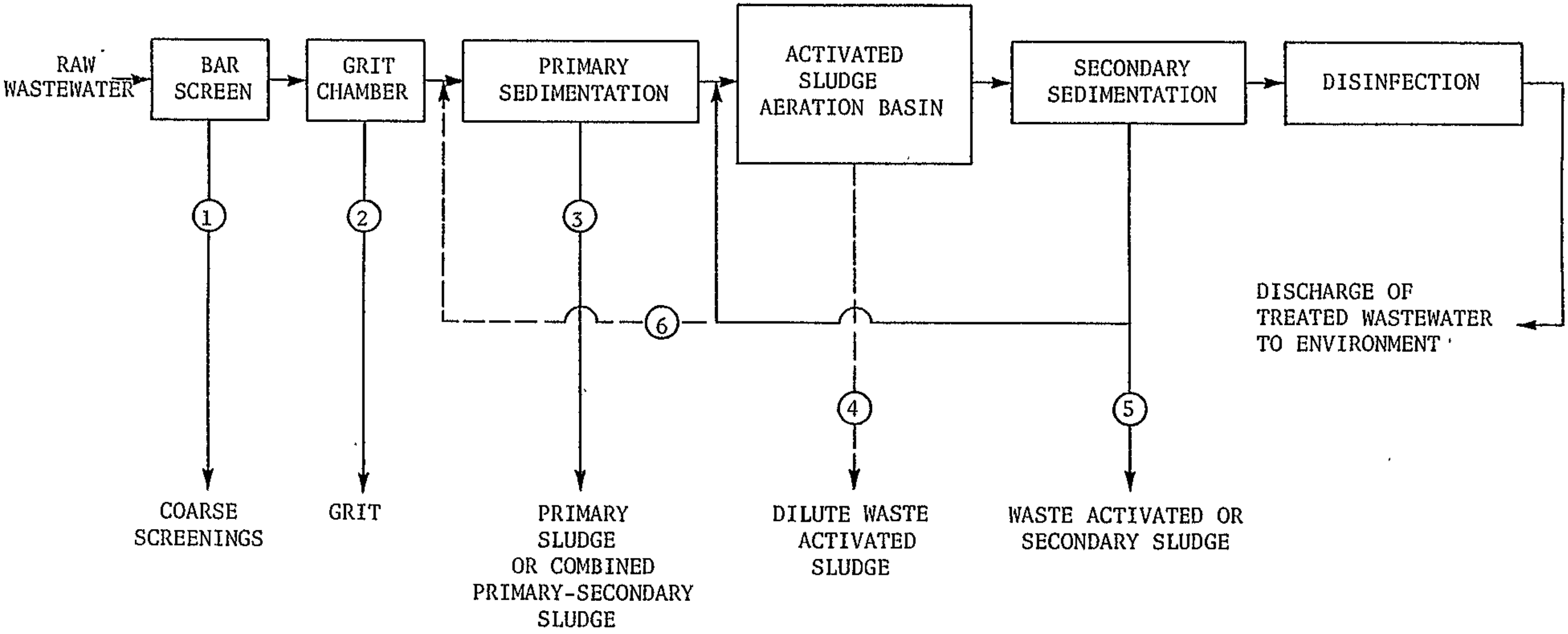

Figure 3. Points of sludge generation for a typical secondary treatment plant employing the activated sludge process.

The first indicated residual solids are coarse screenings from the bar screen process. These solids are usually disposed in either of two ways: (1) They may be mechanically ground into a particle size range such that they will pass through the bar screen when reintroduced into the wastewater. (In this case the coarse screenings are converted to settleable solids and removed during primary sedimentation.) (2) In the second case the screenings, because of their large size range and relatively small volume, are disposed of separately from the more voluminous primary and secondary sludges. Commonly the screenings are incinerated or buried in a sanitary landfill in the second option. In either case, coarse screenings are not subject to disposal by ocean dumping as a separately identifiable type of residual solid and therefore will not be further discussed.

The second source of residual solids is the grit chamber, shown as point 2 of figure 3. Because grit is composed of heavy inorganic solids such as sand and gravel, it is highly abrasive to mechanical devices, especially pumps and associated piping. For this reason grit is removed early in the treatment system to prevent damage to downstream wastewater- or sludge-processing equipment. The grit is then commonly washed to remove putrescible organic matter and buried in a sanitary landfill. Since grit is generally disposed of separately from primary and secondary sludges and is generated in small quantities relative to these sludge types, it will not be discussed further.

In terms of quantities generated and degree of difficulty in processing and final disposal, primary and secondary sludges are the types of chief concern. Primary sludge is discharged from the primary sedimentation basin, shown as point 3 of figure 3. Secondary or biological sludge is recovered in the secondary sedimentation basin. With the activated sludge process, excess microorganisms may be discharged from the bottom of the secondary sedimentation basin (point 5), directly from the aeration basin (point 4), or to the primary sedimentation tank (point 6, fig. 3). In the latter case, the wasted biological solids settle with primary solids and are removed in combination with the primary sludge. In the case of discharge at point 4, the biological solids are dilute because they have not undergone the thickening which usually occurs in the bottom of a sedimentation basin. Therefore, the dilute solids are discharged to a sludge thickener to increase the solids concentration of the waste secondary sludge.

While figure 3 illustrates an activated sludge process, other common aerobic biological wastewater treatment processes such as trickling filters or rotating biological contactors also generate secondary sludge. Such sludges may be discharged at points 5 or 6, with 5 being more common. In both processes the microorganisms are attached to a support medium, but microbial mass is continually sloughed off the medium as new growth occurs. Such fixed-growth processes do not have the option of discharging biological solids at point 4.

While figure 3 illustrates only primary and secondary wastewater treatment processes, tertiary processes also discharge solids in many instances. For example, biological nitrification-denitrification processes for nitrogen removal generate biological sludges while precipitation processes for phosphorus removal generate inorganic chemical sludges. Tertiary processes and their sludges will be of importance in the future, but there are relatively few systems in large scale use today. Data from the U.S. Environmental Protection Agency (1974) indicated only 992 out of 21,011 municipal wastewater treatment plants had any type of tertiary processes. Based on a survey of wastewater treatment plants utilizing ocean disposal of sludge in EPA regions II and III, described later in this report, no tertiary systems were found to exist. Therefore, the remainder of this report concentrates on primary and secondary sludges.

2.2.2. Sludge generation rates. - Major factors influencing the quantities of sludges produced and their characteristics include influent wastewater characteristics, degree of wastewater treatment required, unit processes selected, design of the unit processes, and the operating mode (ref. 16). Because of these factors, reported sludge generation rates span a great range of values. In general, quantities of sludge generated from municipal wastewater treatment plants in the United States approach 54.5 kg/capita/year (120 lb/capita/year) or over 11.8 million metric tons/year on a dry solids basis (ref. 17). By categories of wastewater treatment processes, typical dry solids production figures include 0.054 kg/capita/day (0.12 lb/capita/day) and 0.036 kg/capita/day (0.08 lb/capita/day) for primary and secondary treatment, respectively (ref. 18).

Table 4 lists typical sludge generation rates, in terms of both weight and volume, for primary sedimentation sludge and the most common biological secondary treatment processes. In general, primary sludge is produced at the greater rate in terms of weight per unit volume of wastewater treated. In contrast, when quantified in terms of sludge volume per unit of wastewater treated, activated sludge is most significant. This greater volume is due to the dilute nature of waste activated sludge which results in operating difficulties with solids handling processes such as anaerobic digestion. This high volumetric generation rate has taken on added importance since Federal legislation mandated secondary treatment performance for all municipal wastewater treatment plants in the United States.

Table 4. Typical wastewater sludge generation rates.

| Treatment Process | Dry Solids, g/cubic m | | | | |
|---|---|---|---|---|---|
| | (Ref. 13) | | (Ref. 16) | (Ref. 17) | (Ref. 19) |
| | Range | Typical | Mean | Mean | Mean |
| Primary Sedimentation | 110-170 | 150 | 120 | 150 | 108-144 |
| Activated Sludge | 70-100 | 85 | 84 | 270 | 72-108 |
| Trickling Filter | 55- 90 | 70 | 78 | 57 | 48-108 |

| Treatment Process | Volume, cubic m/$10^6$ cubic m of Wastewater Treated | |
|---|---|---|
| | (Ref. 19) | (Ref. 20) |
| | Range | Range |
| Primary Sedimentation | 2,500-3,500 | 2,440-3,530 |
| Activated Sludge | 15,000-20,000 | 14,600-19,400 |
| Trickling Filter | 400-1,500 | 530-750 |

## 2.3. Sludge Characteristics

In order to understand processes for municipal sludge treatment and disposal, including ocean dumping, it is necessary to know the characteristics of the sludges being processed. As previously discussed, the most important factor controlling sludge characteristics is the origin of the solids. Another critical factor is the amount of aging or elapsed time since generation which has taken place. The characteristics of sludges begin to change the moment they are formed, largely as a result of microbiological activity and chemical reactions.

Finally, sludge characteristics depend on the type of processing which has occurred since generation and collection. Sludges can either be classified as "raw" or "processed." Raw refers to sludge which has not undergone any type of stabilization process which alters the organic characteristics of the sludge. The most commonly used stabilization process is anaerobic digestion, and the final processed solids are referred to as "digested sludge." Processed sludges are those which have undergone some sort of processing since generation, including stabilization methods such as anaerobic digestion.

The purpose of this section is to present and contrast the characteristics of raw primary and secondary wastewater sludges. To fulfill the stated objectives of this report, an examination of the characteristics of anaerobically digested sludges is also nesessary. This examination will be presented in section 3 of this report, which discusses sludge treatment processes.

2.3.1. General sludge characteristics. - The properties of wastewater sludges may be divided into three broad classifications: physical, chemical, and biological. Figure 4, modified from Carnes and Eller (ref. 21), illustrates the common subdivisions of these characteristics. For the purpose of this study a detailed review of each characteristic shown in Figure 4 is not necessary. Such information may be found in reference work by Sawyer and McCarty (ref. 22), the American Public Health Association (ref. 23), Vesilind (ref. 24), and Hecht et al. (ref. 17). The categories of sludge characteristics considered most important from the standpoint of sludge treatment processes and ultimate disposal include:

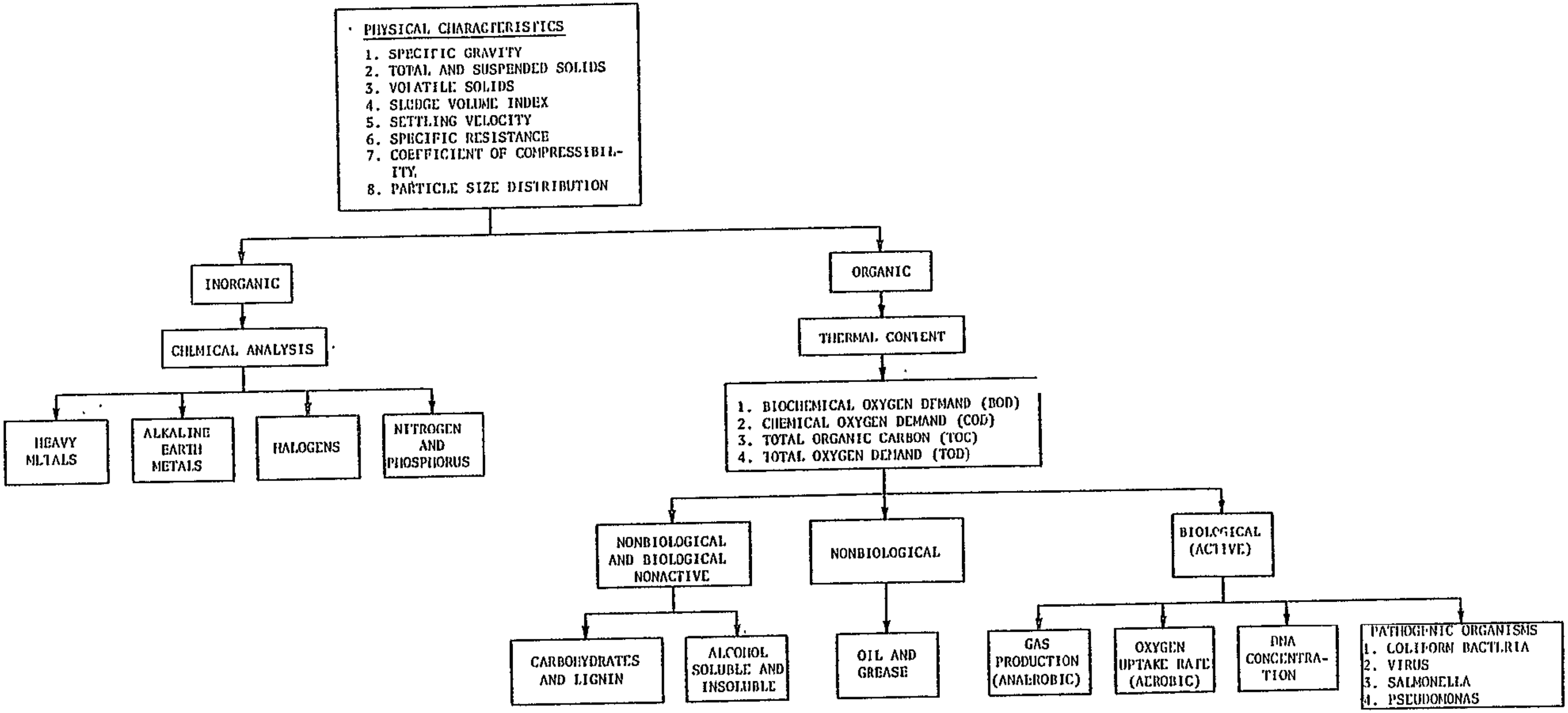

Figure 4. Analysis of wastewater sludge (ref. 21).

(1) oxygen demand (BOD, COD, TOC, TOD),
(2) nutrient content (nitrogen and phosphorus),
(3) solids content,
(4) heavy metals and toxic organics content, and
(5) pathogenic organism content.

For ocean disposal problems, the physical sludge properties which are of interest include bulk density, percentage of total solids, density of dry solids, particle size distribution, and settling characteristics (ref. 25).

The major characteristic complicating the processing and ultimate disposal of wastewater sludges is their water contents or percent total solids. The largest expense in sludge treatment is directly related to the tons of water associated with each ton of solids. A thin waste activated sludge from biological treatment may contain over 100 tons of water associated with each ton of solids (ref. 20). The amount of water associated with each ton of solids, or percent total solids, is not a fundamental property of different sludge types. Instead, it is directly a function of the conditions of generation and any subsequent sludge-processing operations.

2.3.2. Characteristics of primary and secondary sludges. - With regard to the objectives of this study, it is most important that the characteristics of primary and secondary sludges be defined and constrasted. Table 5 gives a general description of the characteristics for primary sedimentation sludge and the two most common types of secondary sludge.

The most important distinction to be recognized from table 5 is the nature of the solids particles themselves. Primary sludge is composed of raw organic materials settled from the wastewater, the solid particles being coarse in size and containing some fibrous matter. The biological characteristics of primary sludge relate to its content of pathogenic, or disease causing, organisms associated with the raw wastewater solids.

Secondary or biological sludges, in contrast, are composed almost solely of solids particles of microbial origin. For example, activated sludge is normally comprised of 60 to 90 percent or more cellular organic material (ref. 26). These particles of bacterial cellular material aggregate through

Table 5. General description of primary and secondary sludges (ref. 44).

| Sludge Type | Description |
|---|---|
| Primary Sludge | A gray-colored, greasy, odorous slurry of settleable solids accounting for 50 to 60 percent of the suspended solids applied in the wastewater and tank skimmings. Scum is usually less than one percent of the settled sludge volume. Primary sludges can be dewatered readily after chemical conditioning because of their fibrous and coarse nature. Typical solids concentrations in raw primary sludge are six to eight percent. The portion of volatile solids varies from 60 to 80 percent. |
| Activated Sludge | A dark brown, flocculent suspension of active microbial masses, inoffensive when fresh but turning septic rapidly because of biological activity. Solids in the mixed liquor from an activated sludge process settle slowly, forming a rather bulky sludge of high water content. The concentration of activated sludge returned from secondary sedimentation ranges from 0.5 to 2.0 percent suspended solids with a volatile fraction of 0.7 to 0.8. High water content, resistance to gravity thickening, and the presence of active microbial floc make this sludge difficult to handle. |
| Trickling Filter Sludge | Also termed trickling filter humus, this sludge is dark brown in color, flocculent, and relatively inoffensive when fresh. The suspended particles are fragments of biological growth washed from the filter media. Although it exhibits good settleability, the sludge does not compact to a high density. For this reason and the fact that solids discharge from the filter media is irregular, settled sludge is returned to the head end of the wastewater treatment plant. Thus the sludge is resettled in the primary sedimentation process with raw wastewater organic solids. The combined sludge has a solids content of four to six percent, which is only slightly thinner than primary sludge only. |

bioflocculation into masses which are large enough to settle under the influence of gravity. Thus, the floc particles are generally small in size, and the particle size distribution lacks the larger solids which would be found in primary sludge. The essential difference between primary and secondary sludges is the origin of the solids fraction. For primary sludge the solids are brought in with the influent wastewater and are characteristic of the types of industries, commercial establishments, and residences discharging to the sewer system. These contributing sources make primary sludge an extremely heterogeneous mixture of solids types and particle sizes. For secondary sludges the solids are generated by biological treatment processes and are characteristic of the particular process being used and its mode of operation.

With these significant distinctions understood it is important to define in more specific and quantitative terms the characteristics of primary and secondary sludges. Tables 6, 7, and 8 illustrate typical characteristics of unprocessed primary, activated, and trickling filter sludges, respectively. Because of the relatively greater number of wastewater treatment plants utilizing the activated sludge process for secondary treatment, the most meaningful comparison can be drawn between primary sludge and activated sludge.

Table 6. Typical characteristics of primary sludge.

| Characteristic | Range | Typical | Ref. |
|---|---|---|---|
| Total dry solids (TS), % | 2.0-8.0 | 5.0 | (13) |
| Volatile solids (% of TS) | 6.0-8.0 | 65 | (13) |
| Grease and fats (ether-soluble, % of TS) | 6.0-30.0 | -- | (13) |
| Protein (% of TS) | 20-30 | 25 | (13) |
| Nitrogen (N, % of TS) | 1.5-6.0 | 4.0 | (13) |
| Phosphorus ($P_2O_5$, % of TS) | 0.8-3.0 | 2.0 | (13) |
| Potash ($K_2O$, % of TS) | 0-1.0 | 0.4 | (13) |
| Cellulose (% of TS) | 8.0-15.0 | 10.0 | (13) |
| Iron (not as sulfide, % of TS) | 2.0-4.0 | 2.5 | (13) |
| Silica ($SiO_2$, % of TS) | 15.0-20.0 | -- | (13) |
| pH | 5.0-8.0 | 6.0 | (13) |
| Alkalinity (mg/l as $CaCO_3$) | 500-1500 | 600 | (13) |
| Organic acids (mg/l as HAc) | 200-2000 | 500 | (13) |
| Thermal content (MJ/kg)[b] | 14-23 | 16.5[a] | (13) |
| Specific gravity of sludge solids | -- | 1.4 | (13) |
| Specific gravity of sludge | -- | 1.02 | (13) |
| Coefficient of compressibility | -- | 0.87 | (17) |
| Specific resistance ($sec^2/g \times 10^7$) | 1310-2110[a] | -- | (17) |
| Virus (PFU/100 ml) | -- | 7.9 | ( 3) |
| Coliform ($10^6$/100 ml) | -- | 11.4 | ( 3) |
| Salmonella (per 100 ml) | -- | 460 | ( 3) |
| Pseudomonas (per 100 ml) | -- | 46,000 | ( 3) |

[a] Based on 65 percent volatile matter

[b] MJ/kg × 429.92 = Btu/lb

Table 7. Typical characteristics of activated sludge.

| Characteristic | Range | Typical | Ref. |
|---|---|---|---|
| Total dry solids (TS), % | 0.50-1.50 | 0.75 | (13) |
| Volatile solids (% of TS) | 60-80 | 70 | (13) |
| Grease and fats (ether-soluble, % of TS) | 5-12 | -- | (17) |
| Protein (% of TS) | 32-41 | -- | (17) |
| Nitrogen (N, % of TS) | 4.8-6 | 5.6 | ( 3) |
| Phosphorus ($P_2O_5$, % of TS) | 3.1-7.4 | 5.7 | ( 3) |
| Potash ($K_2O$, % of TS) | 0.3-0.6 | -- | ( 3) |
| Cellulose (% of TS) | -- | 7.0 | (17) |
| Iron ($Fe_2O_3$, % of TS) | -- | 7.15 | (17) |
| Silica ($SiO_2$, % of TS) | -- | 8.45 | (17) |
| pH | 6.5-8.0 | 7.0 | (17) |
| Thermal content (MJ/kg) | -- | 15.2 | (17) |
| Specific gravity of sludge solids | -- | 1.25 | (13) |
| Specific gravity of sludge | -- | 1.005 | (13) |
| Coefficient of compressibility | 0.60-0.79 | -- | (17) |
| Specific resistance ($sec^2/g \times 10^7$) | -- | 2800 | (17) |
| Coliform ($10_6$/100 ml) | 2.0-20 | -- | (27) |
| Salmonella (per 100 ml) | 74-9300 | -- | (27) |
| Pseudomonas (per 100 ml) | 1100-24000 | -- | (20) |

Table 8. Typical characteristics of trickling filter sludge.

| Characteristic | Range | Typical | Ref. |
|---|---|---|---|
| Total dry solids (TS), % | 1.0-3.0 | 1.5 | (13) |
| Volatile solids (% of TS) | 50-80 | -- | ( 3) |
| Nitrogen (N, % of TS) | 1.5-5 | 3 | ( 3) |
| Phosphorus ($P_2O_5$, % of TS) | 1.4-4 | 3 | ( 3) |
| Potash ($K_2O$, % of TS) | 0-1 | -- | ( 3) |
| Specific gravity of sludge solids | -- | 1.45 | (13) |
| Specific gravity of sludge | -- | 1.025 | (13) |
| Coefficient of compressibility | -- | 0.80 | (17) |
| Coliform ($10^6$/100 ml) | | 11.5 | ( 3) |
| Salmonella (per 100 ml) | | 93 | ( 3) |
| Pseudomonas (per 100 ml) | | 11,000 | ( 3) |

The most important differences are the greater solids content and lower specific resistance of primary sludge. Both sets of values reflect basic differences in particle characteristics of the sludges. Primary sludge is made up of coarse solids which compact more readily than bulky flocculant solids, thus producing a higher solids content. The coarse nature of the solids is also shown by the lower specific resistance value for primary sludge. Specific resistance is a measure of the difficulty with which a sludge may be dewatered by vaccum filtration. Higher specific resistance values indicate a sludge that is more difficult to dewater. Typically, the smaller the particle size of the solids, the higher the specific resistance (ref. 26). Therefore the coarser nature of primary solids results in a lower specific resistance than that resulting from activated sludge solids. Activated sludge is finer in particle size than primary sludge (ref. 26).

The flocculant nature of the biological solids comprising activated sludge also results in a smaller degree of compaction and thus a lower solids content, only 0.5 to 1.5 percent. This is also the result of a lower bulk density for the activated sludge solids, shown by the lower specific gravity than that for primary sludge solids. The specific gravity, and thus bulk density, of the total sludge mixture (solids + water) is lower for activated sludge.

Another important group of characteristics for wastewater sludges is the heavy metals concentrations, as these directly control options for ultimate solids disposal. Table 9 lists typical elemental analyses for primary and activated sludge, including the common heavy metals such as chromium, cadmium, copper, lead, mercury, nickel, and zinc. Comparisons of metal concentrations between the two sludge types is not meaningful since the major governing factor is the nature of the waste originally treated. Wastewaters which are of industrial origin usually exhibit higher metals concentrations and pass this trait on to resulting sludges. Additional data showing elemental analyses of various sludge types may be found in Appendix A.

2.3.3. Particle size. - As mentioned when discussing general sludge properties, particle size distribution is of interest in ocean disposal problems. This is especially true since the amount of turbidity detected in a water column varies directly with particle size (ref. 28). Such turbidity-causing particles alter the spectral response of the ocean water surface and provide the basis for remote sensing of wastewater sludge ocean disposal.

Wastewater sludge particle size distributions have not been a widely studied or measured characteristic. Particles in sludge vary not only in size but also in consistency and shape. Therefore, it is extremely difficult

Table 9. Elemental analysis of primary and activated sludge (ref. 3).

| | Primary Sludge | | | Activated Sludge | | |
|---|---|---|---|---|---|---|
| Element | Average[a] | Range[a] | No. in Sample | Average[a] | Range[a] | No. in Sample |
| Aluminum | 5.10 | 10.78-1.83 | 3 | 10.0 | 17.0-4.35 | 3 |
| Arsenic | 1.24 | 1.49-0.83 | 3 | 1.20 | 22.22-0.101 | 3 |
| Barium | 2.25 | 5.0-0.11 | 11 | 1.15 | 3.0-0.22 | 4 |
| Beryllium | 0.0025 | 0.0030-0.0017 | 3 | 0.0035 | 0.0044-0.0026 | 2 |
| Boron | 0.104 | 0.15-0.07 | 11 | 0.070 | 0.22-0.006 | 9 |
| Cadmium | 0.188 | 0.30-0.0034 | 4 | 0.35 | 0.44-0.26 | 2 |
| Calcium | 0.063 | 0.10-0.01 | 7 | 13.0 | 18.0-9.0 | 7 |
| Chromium | 2.05 | 9.0-0.08 | 15 | 4.31 | 17.0-0.1 | 8 |
| Cobalt | 0.217 | 0.5-0.05 | 6 | 0.0016 | 0.0016 | 1 |
| Copper | 2.00 | 6.0-0.0083 | 17 | 1.10 | 2.6-0.372 | 13 |
| Iron | 16.1 | 20.0-2.86 | 12 | 40.5 | 96.6-4.83 | 9 |
| Lead | 1.01 | 2.14-0.33 | 3 | 1.52 | 2.09-0.51 | 3 |
| Magnesium | 10.6 | 15.0-5.0 | 8 | 7.04 | 10.9-3.01 | 7 |
| Manganese | 0.781 | 1.0-0.16 | 11 | 0.310 | 0.93-0.055 | 9 |
| Mercury | 0.0046 | 0.006-0.0030 | 2 | 0.016 | 0.020-0.012 | 2 |
| Molybdenum | 0.362 | 1.0-0.05 | 11 | 0.197 | 0.89-0.006 | 8 |
| Nickel | 0.522 | 2.0-0.0014 | 17 | 0.378 | 2.0-0.04 | 8 |
| Phosphorus | 3.78 | 6.83-1.49 | 3 | 19.9 | 32.2-11.07 | 8 |
| Potassium | | | | 4.21 | 7.16-2.49 | 6 |
| Silicon | | | | 39.5 | 39.5 | 1 |
| Silver | 0.243 | 1.0-0.08 | 11 | 0.150 | 0.22-0.1 | 3 |
| Sodium | 3.96 | 10.0-0.5 | 8 | 4.44 | 7.88-1.0 | 2 |
| Strontium | 0.13 | 0.14-0.12 | 3 | 0.155 | 0.21-10.0 | 2 |
| Sulfur | | | | 10.1 | 11.6-7.6 | 6 |
| Tin | 0.95 | 2.0-0.5 | 8 | 0.5 | 0.5 | 1 |
| Titanium | 14.8 | 20.0-5.0 | 8 | 11.8 | 20.0-0.50 | 3 |
| Vanadium | 2.09 | 15.0-0.3 | 11 | 0.70 | 0.89-0.51 | 3 |
| Zinc | 6.87 | 25.0-0.34 | 18 | 3.29 | 6.3-0.13 | 13 |
| Zirconium | 1.72 | 10.9-0.3 | 8 | 10.0 | 10.0 | 1 |

[a] Values given are number of mg/g dried sludge.

to charactize sludges by particle size (ref. 24). Further complications arise because sludge particle sizes change with time or age of the sludge sample and are a direct function of the test procedure used. Changes occurring with increasing time are the result of microbiological activity and chemical reactions. In most cases these changes are impossible to stop, with potential preservatives or inhibitors possibly causing particle size changes themselves.

The size of particles, especially irregularly shaped ones, depends to a great extent on how particle size is defined. Various size classification systems for wastewater solids have been proposed. One of the most common systems is illustrated in table 10. The size distribution of wastewater solids is a function of the types of contributors (domestic, commercial, industrial) to the sewerage system. Also, the treatment processes which collect raw solids or generate new solids (e.g., biological processes) influence size distribution. Once the solids have been collected to form the various sludge types, the particle size distribution, just as percent total solids, becomes a direct function of the type of sludge-processing operations which follow. It is impossible to compare particle size distributions among sludges if the stage or degree of processing and the method of measurement are not known in detail. For example, particle fractionation by centrifugation depends on particle density; filtration depends on the maximum dimension of a particle; a Coulter Counter analysis is based on particle volume, and absorption methods are based on the surface area of the particle. Consequently, even for moderately irregular particles, the size of a particle may vary by a factor greater than two depending on how it was measured (ref. 30). In summary, it is not proper to measure sludge particle size unless the test procedure and past history of the sludge are defined.

Table 10. Typical wastewater solids classification system (ref. 29).

| Solid | Particle Size (μm) |
|---|---|
| Settleable | $\geq 100$ |
| Supracolloidal | 1 to 100 |
| True colloidal | 0.001 to 1 |
| Dissolved | $\leq 0.001$ |

Of particular importance in the ocean disposal of wastewater sludges is the further problem of how to size fragile flocculated particles, such as those which are prevalent in activated sludge, and which result when any type of sludge is dispersed in seawater. The most commonly used classification system of flocculated particles uses three levels of floc aggregation: primary particles, flocs, and aggregates (ref. 30). The primary particles are the building blocks or destabilized particles existing prior to orthokinetic flocculation. Flocs are agglomerations of primary particles. Aggregates are defined as clusters of flocs which are thought to be loosely held together primarily by mechanical enmeshment of projections or tentacles extending outward in a random manner from the main floc body. Flocs have also been defined on the basis of size. Robeck (ref. 31) defined flocs as particles having diameters in the range of 100 to 2000 micrometers (μm). Finstein and Heukelekian (ref. 32) defined flocs as having a size greater than 20 μm since they found activated sludge flocs to have diameters between 20 and 200 μm.

Measurement of floc size is difficult due to the fragile nature of the flocs and the many environmental factors which cause flocculation or deflocculation. Floc formation is time dependent, resulting in variation in particle size with time (ref. 24). Even if samples are taken at a known stage of the flocculation process, it is unlikely that the particle size distribution will not change during sample storage before analysis, or during the actual measurement step. Biological factors, pH, and trace quantities of chemical impurities can have significant affects on the physical and chemical properties of flocs (ref. 30).

Many studies of wastewater sludge dispersion during ocean disposal have utilized the Coulter Counter method to measure sludge particle size (refs. 25, 33, 34). This technique has not been widely applied in sanitary engineering to analyze wastewater sludges, but Ham and Christman do discuss its application for measuring floc size in water treatment (ref. 35). The major limitation of the method appears to be its inability to measure large settleable sludge particles (> 100 μm) and fragile sludge flocs. Browne and Callaway (ref. 25) applied the Coulter Counter method to their study of the physical and settling characteristics of sewage sludge and stated:

> "Uncertainty exists in the correlation of floc size to particle size as determined with the Coulter Counter. Observation of settling flocs indicate that they are much too large compared to the instrumentally determined particle size. It is assumed that the sampling procedure, sample preparation, and analysis disaggregates the floccules into more discrete particles, the volume of which is determined instrumentally."

Their study of anaerobically digested sludges from New York area wastewater treatment plants found a mean elementary particle equivalent diameter range of 5 to 25 µm, which is below or at the lower end of size ranges previously cited for floc. Microscopic examination of the same sludges revealed a very heterogeneous suspension of particles with no dominant shape or size.

The primary interest in sludge solids particle size distributions in sanitary engineering stems from the relationship to the degree of difficulty encountered when sludges are mechanically dewatered. Bargman et al. (ref. 36) found particle size along with compressibility to be the most important variables affecting filterability of digested sludges. Specific resistance is, in effect, a measure of the relative dewaterability of a sludge. Increasing values indicate an increasing degree of difficulty in removing water (ref. 30). In general, specific resistance values increase as sludge particle sizes decrease (ref. 26). Table 11 illustrates the relative difficulty of removing water from an anaerobically digested primary sludge containing various particle size fractions. The figures demonstrate that the specific resistance to filtration of the unfractionated sludge is dominated by the specific resistance of the particles under 5 µm in size, even though this material constitutes only about 14 percent by weight of the total solids.

Table 11. Sludge dewatering as a function of particle size (ref. 26).

| Mean Particle Diameter (µm) | Specific Resistance ($sec^2/g$) | Coefficient of Compressibility | Percent of Total Particles |
|---|---|---|---|
| Original, unfractionated sample | $10.4 \times 10^9$ | 0.66 | - |
| > 100 | $2.3 \times 10^9$ | 0.73 | 10.2 |
| 5-100 | $4.6 \times 10^9$ | 0.70 | 75.5 |
| 1-5 | $13.8 \times 10^9$ | 0.42 | 8.5 |
| Below 1 | - | - | 5.9 |

The effectiveness of organic and inorganic chemical coagulants used to condition sludges for mechanical dewatering has been attributed to their ability to increase particle size through flocculation (ref. 30). The influence of chemical conditioning on specific resistance is shown in table 12. For both raw primary sludge and anaerobically digested primary sludge, the chemically conditioned or coagulated sludges exhibit lower specific resistance values.

Table 12. Influence of chemical conditioning on specific resistance (ref. 26).

| Sludge Type | Specific Resistance ($sec^2/g$) |
|---|---|
| Raw primary sludge | $10 - 30 \times 10^9$ |
| Raw primary sludge, chemically conditioned | $3 - 10 \times 10^9$ |
| Anaerobically digested primary sludge | $3 - 30 \times 10^9$ |
| Anaerobically digested and chemically conditioned primary sludge | $2 - 20 \times 10^9$ |

A definitive study on the relationship of sludge particle size distribution and sludge dewatering has been performed by Karr (ref. 30). The data from this study can be used to compare particle size distributions for primary and activated sludges. Figure 5 illustrates the fractionation procedure which was used to classify solids into five categories: rigid settleable solids, fragile settleable solids, supracolloidal solids, true colloidal solids, and dissolved solids. Actual particle size ranges for these categories, which were dependent on commercially available mesh and filter sizes, are also shown in figure 5. Definition of a size range for the fragile settleable solids was not possible since these solids deformed or broke apart and passed through the 104-μm mesh. They were then recovered after flocculation and gravity sedimentation. The reader is referred to Karr's research (refs. 30, 37) for additional information on this procedure.

Table 13 presents average particle size distributions and specific resistance values for raw primary and activated sludge based on 6 samples of primary sludge and 13 samples of activated sludge. A total of 5 wastewater treatment plants, ranging in size from 3,785 to 76,000 $m^3/d$ (1 to 20 gal × $10^6/d$) were sampled. The data show that primary sludge had the highest concentration of rigid settleable solids (primarily cellulose) and the

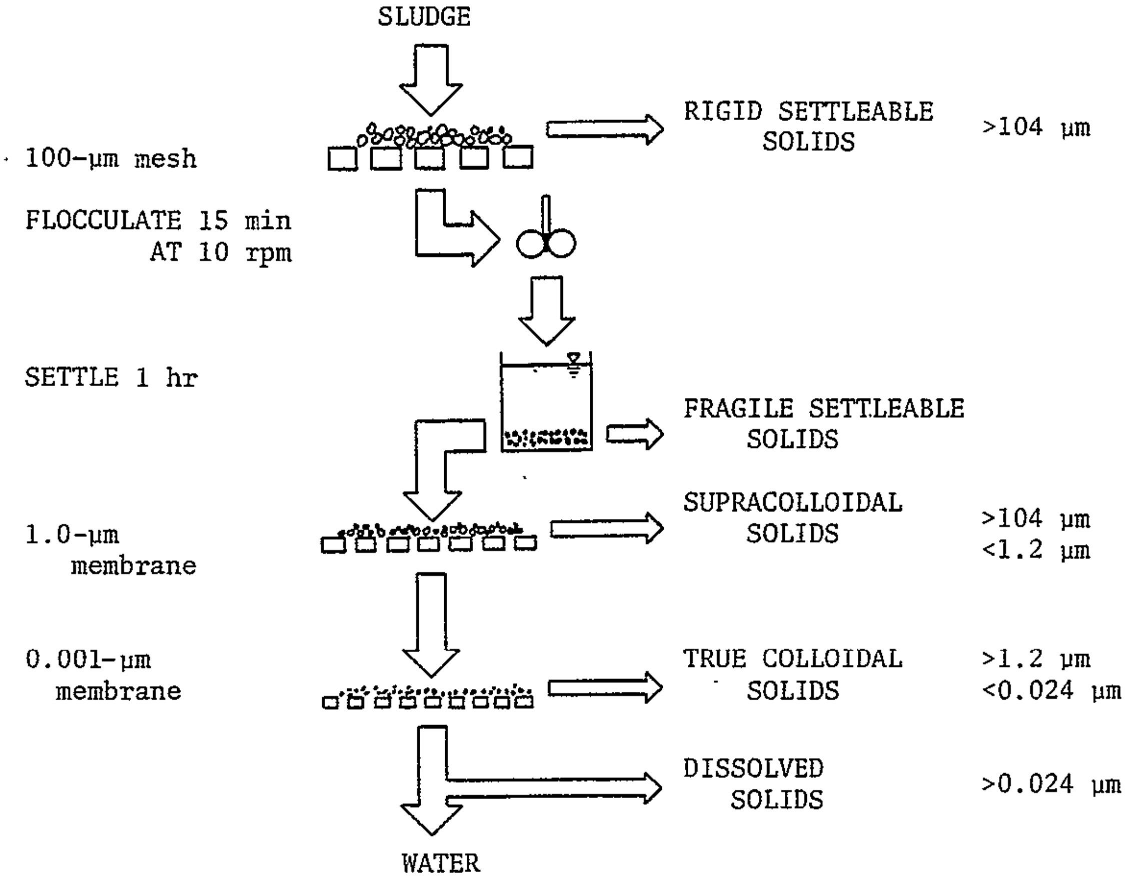

Figure 5. Sludge fractionation procedure of Karr (ref. 30).

lowest concentration of fragile settleable solids. Activated sludge had smaller values for supracolloidal, true colloidal, and dissolved solids.

Table 13. Average particle size characteristics for primary and activated sludges (ref. 30).[a]

| Measurements | Primary Sludge | Activated Sludge |
|---|---|---|
| Specific resistance, m/kg[b] | $21.8 \times 10^{13}$ | $4.8 \times 10^{13}$ |
| pH | 5.8 | 6.0 |
| Solids, mg/l | | |
| Total | 9,698 | 8,841 |
| Rigid settleable | 6,452 | 1,920 |
| Fragile settleable | 2,320 | 6,587 |
| Suprocolloidal | 355 | 84 |
| True colloidal | 45 | 7 |
| Dissolved | 526 | 243 |

[a] Note: all values are averages.

[b] Specific resistance at 15 in. Hg, T = 21°C.

Tables 14, 15, and 16 indicate the effects of mixing, storage time, and pH on sludge particle size distributions and dewaterability. In general these experiments reveal that mixing, biological activity, and pH changes can alter particle size distributions by decreasing rigid settleable solids and increasing fragile settleable, supracolloidal, true colloidal, and dissolved solids.

Table 14. Effect of mixing on particle size distribution and dewaterability of primary sludge (ref. 30).

| Measurement | Before Mixing (pH = 5.6) | Mixed 5 min. | Mixed 20 min | Reflocculated 20 min |
|---|---|---|---|---|
| Specific resistance, m/kg[a] | $7.8 \times 10^{13}$ | $38.7 \times 10^{13}$ | $56.6 \times 10^{13}$ | $52.0 \times 10^{13}$ |
| Solids, mg/l | | | | |
| Total | 7,752 | 7,752 | 7,752 | 7,752 |
| Rigid settleable | 5,100 | 4,400 | 3,984 | 3,877 |
| Fragile settleable | 2,205 | 2,540 | 2,715 | 2,890 |
| Supracolloidal | 189 | 498 | 620 | 557 |
| True colloidal | 48 | 87 | 162 | 186 |
| Dissolved | 210 | 227 | 271 | 262 |

[a] Specific resistance at 15 in. Hg, T = 21°C.

Table 15. Effect of storage time on particle size distribution and dewaterability on nonaerated activated sludge (ref. 30):

| Measurement | Base Case | Elapsed Time (Days) 1 | Elapsed Time (Days) 5 |
|---|---|---|---|
| Specific resistance, m/kg[a] | $1.5 \times 10^{13}$ | $2.3 \times 10^{13}$ | $4.2 \times 10^{13}$ |
| pH | 6.6 | 6.5 | 6.5 |
| Solids, mg/l | | | |
| Total | 8,517 | 8,705 | 7,890 |
| Rigid settleable | 3,016 | 3,140 | 1,738 |
| Fragile settleable | 5,216 | 5,191 | 5,650 |
| Supracolloidal | 30 | 52 | 146 |
| True colloidal | 1 | 18 | 16 |
| Dissolved | 254 | 304 | 340 |

[a] Specific resistance at 15 in. Hg, T = 21°C.

Table 16. Effect of pH on particle size distribution and dewaterability for activated sludge (ref. 30).[a]

| Measurement | pH = 3 | pH = 5 | pH = 5.3 (As Is) | pH = 6 | pH = 8 | pH = 11 |
|---|---|---|---|---|---|---|
| Specific resistance, m/kg[b] | $1 \times 10^{13}$ | $4.8 \times 10^{13}$ | $5.3 \times 10^{13}$ | $6.3 \times 10^{13}$ | $10.2 \times 10^{13}$ | $146 \times 10^{13}$ |
| Solids, mg/l | | | | | | |
| Total | 9,030 | 8,804 | 8.714 | 8,724 | 8,782 | 9.031 |
| Rigid settleable | 4,626 | 2,115 | 2,005 | 2,010 | 1,986 | 1,592 |
| Fragile settleable | 3,708 | 6,306 | 6,335 | 6,315 | 6,125 | 5,341 |
| Supracolloidal | 10 | 64 | 77 | 99 | 134 | 490 |
| True colloidal | 6 | 10 | 7 | 7 | 27 | 1,098 |
| Dissolved | 680 | 289 | 290 | 291 | 510 | 1,510 |

[a] Note: $H_2SO_4$ used to lower pH; NaOH used to raise pH.

[b] Specific resistance at 15 in. Hg, T = 21°C.

Karr (ref. 30) concluded from his research that changes in sludge dewaterability (as measured by specific resistance values) that are attributed to changes in pH, biological degradation, mixing, and chemical conditioning may be explained on the basis of changes that these factors bring about in the particle size distribution. His results also indicate that supracolloidal solids (1 to 100 μm) most influence sludge dewatering characteristics.

2.3.4. Settling Velocity. - Figure 3 indicates that settling characteristics of wastewater sludges, specifically settling velocity, are commonly determined for engineering purposes. In sanitary engineering, settling velocity is required to properly design sedimentation basins for gravity solids/liquid separation and sludge thickening (ref. 38). Sludge settling characteristics are also of importance in ocean disposal problems because of their influence in dispersion patterns and rates (ref. 25). It is therefore unfortunate that typical sludge settling velocities determined in sanitary engineering by techniques such as those described by Eckenfelder and Ford (ref. 38) are not applicable to ocean disposal problems.

There are two major factors which influence sludge settling velocities and which contribute to this lack of applicability. These factors are particle or solids concentration and particle-particle interactions, or flocculation. Typical sludge settling tests in sanitary engineering examine suspensions with high solids concentrations. At high concentrations, the solids particles do not settle discretely. Instead they form one large solids matrix which settles as one mass, with a distinct solid/liquid interface. This type of settling has been termed Type III sedimentation or hindered settling (ref. 13). Ocean disposal techniques dilute dumped sludge to the point that Type III sedimentation does not occur. Instead, the dilute suspension of solids particles exhibits significant particle-particle interaction, resulting in particle size growth or flocculation. The settling of flocculent suspensions of this type has been termed Type II sedimentation, and quantification of this behavior is important in the design of secondary sedimentation basins. However, such tests have not been performed for sludges suspended in saline solutions by sanitary engineers.

The ability of sludge solids particles to flocculate is directly related to ionic or electrostatic forces between particles (ref. 39). Salt water, with its high ionic strength relative to freshwater or waste waters, greatly influences the flocculation process, as documented by Mead (ref. 39).

For these reasons, typical hindered settling velocities for primary and secondary sludges have not been listed. The reader is referred to the work of Browne and Callaway (ref. 25) for more information on sewage sludge particle growth and settling characteristics in saline waters.

# 3. SLUDGE TREATMENT AND DISPOSAL PROCESSES

## 3.1. Purpose of Sludge Treatment

The end result of the liquid processing system in a modern wastewater treatment plant is the production of a purified effluent which meets discharge standards, but the handling and disposition of the residual solids is just beginning. The majority of contaminants removed during liquid treatment are contained in the resulting sludge. Sludges in their "as generated" or raw state generally possess a number of undesirable properties, including high water, pathogen, and putrescible organic material contents. Such properties give rise to a situation in which it is highly unlikely that sludges can be ultimately disposed in their raw state without adverse environmental effects. Physical, chemical, and biological modifications of sludge quality must occur before environmentally acceptable disposal is realized. The purpose of sludge treatment processes is to bring about these modifications while having minimal impact on the liquid treatment processes in a total wastewater treatment system.

Table 17 describes the seven general categories of sludge treatment operations along with their intended objectives. It must be noted that these operations are not given in their normal sequence of use, nor are they all necessarily applied in any given sludge processing situation.

## 3.2. Sludge Treatment Process Availability

For each general category of sludge treatment operations there are many choices of specific processes available to accomplish the objectives stated in table 17. Table 18 lists the commonly available processes under each sludge treatment category. Many of the processes are capable of satisfying multiple objectives and could be located within more than one category. For example, a thermal reduction technique such as incineration also accomplishes most of the objectives given for stabilization processes. In table 18 the separate processes are listed only once in the category in which they are most commonly recognized.

Table 17. General categories of sludge treatment operations (ref. 26).

| | Category | Objectives |
|---|---|---|
| 1. | Thickening | Increase in solids concentration of liquid sludge by removing water, thus reducing volume |
| 2. | Stabilization | Pathogen destruction, volume and weight reduction, odor and putrescibility control, gas production |
| 3. | Conditioning | Pretreatment to improve dewatering or thickening rate, solids capture, and compactibility by increasing particle size through flocculation, or to modify sludge structure by heat treatment |
| 4. | Dewatering | Water removal for volume and weight reduction to the degree that the mixture is transformed from a liquid to a damp solid state (> 15 percent total solids) |
| 5. | Heat drying | Moisture removal to render sludge dry to the touch and into a relatively free-flowing granular material |
| 6. | Thermal reduction | Reduction in sludge volume and weight through thermal destruction of volatile sludge solids; sterilization may also be achieved |
| 7. | Ultimate disposal | Final disposal of processed sludge, whether in liquid, damp solid, dry solid, or ash form, as a residue to the environment, or as a resource in reuse/recovery applications |

Table 18. Available sludge treatment unit processes (refs. 13, 26).

| | Category | Available Processes |
|---|---|---|
| 1. | Thickening | Gravity thickening<br>Flotation thickening<br>Centrifugation<br>Classification for calcium recovery in lime-precipitated sludges |
| 2. | Stabilization | Chlorine oxidation<br>Lime stabilization<br>Anaerobic digestion<br>Aerobic digestion<br>Pure-oxygen aerobic digestion<br>Composting |
| 3. | Conditioning | Heat treatment<br>Chemical conditioning<br>Elutriation |

(Continued)

Table 18. (Concluded)

| Category | Available Processes |
|---|---|
| 4. Dewatering | Centrifugation<br>Vacuum filtration<br>Pressure filtration<br>Horizontal belt filtration<br>Sand bed drying<br>Lagooning |
| 5. Heat drying | Flash drying<br>Multiple hearth drying<br>Rotary drying<br>Spray drying |
| 6. Thermal reduction | Multiple hearth incineration<br>Fluidized bed incineration<br>Flash combustion<br>Co-incineration with municipal solid wastes<br>Pyrolysis<br>Copyrolysis with municipal solid wastes<br>Wet-air oxidation<br>Recalcination for lime recovery |
| 7. Ultimate disposal | Sanitary landfill disposal<br>Ocean disposal<br>Land application on cropland or for land reclamation |

To attain the objectives of this study it is not necessary to describe theory and influence on sludge characteristics for each of the processes listed in table 18. This type of information may be found in discussions published by Metcalf and Eddy Inc. (ref. 13), Vesilind (ref. 24), and the EPA (ref. 26). The one process of dominant importance to this study is anaerobic digestion, since it is this process which is employed in the City of Philadelphia wastewater treatment plants for sludge stabilization prior to ocean disposal (ref. 40).

Before anaerobic sludge digestion is described in detail, it should prove helpful to examine a process flowsheet for a typical activated sludge treatment system employing anaerobic digestion. Figure 6 illustrates a sludge flowsheet for a plant where the waste activated and primary sludges are removed separately from their respective sedimentation tanks. Being of a very dilute nature (0.50 to 1.50 percent solids), waste activated sludge usually requires thickening to three to six percent solids before undergoing anaerobic digestion. Primary sludge usually contains 4 to 12 percent solids,

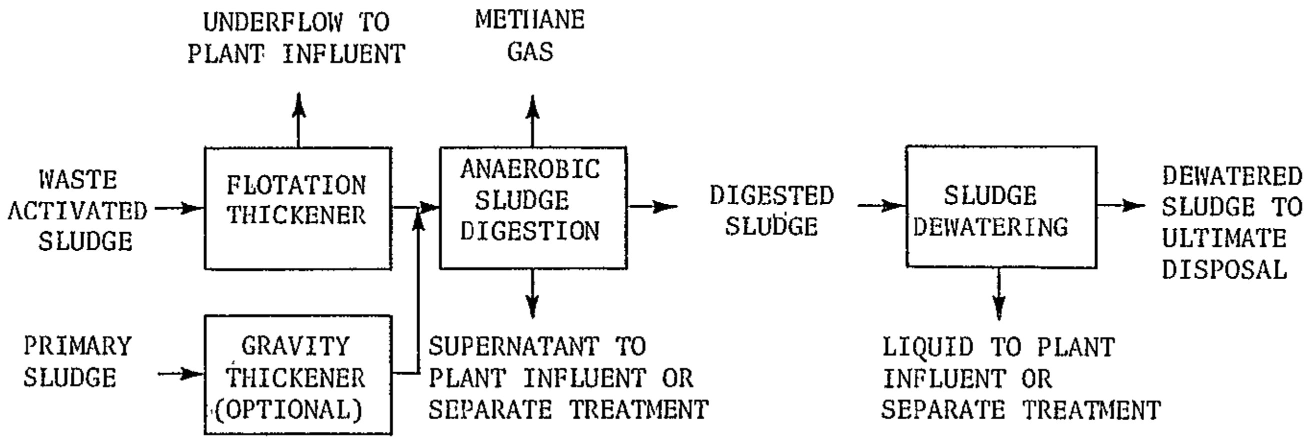

Figure 6. Typical sludge treatment flowsheet for separate sludge sources.

and sludge thickening becomes an optional step. Thickened sludge is fed to the anaerobic digestion process where volatile organic material is converted to methane gas. The digested sludge produced, still in liquid form but now reduced in volatile organic content, is then dewatered to produce a product in solid form. Having sludge which can be handled as a solid increases the ultimate disposal options and can decrease costs by removing the volume and weight otherwise contributed by water. It should be noted, however, that many ultimate disposal methods such as land application and ocean disposal can also utilize liquid digested sludge, depending on specific circumstances.

Figure 7 illustrates a sludge flowsheet for a plant where the excess activated sludge is wasted to the primary sedimentation basins for removal with the primary sludge. The combined waste activated-primary sludge is then fed to the anaerobic digestion process. This flow pattern is employed by the City of Philadelphia at its Northeast Wastewater Treatment Plant.

## 3.3. Anaerobic Digestion Process

Considering all of the sludge treatment processes previously discussed, anaerobic digestion is considered to be the most important with respect to the purpose of this study. This is because the process is employed to stabilize those municipal wastewater sludges which have been observed during remote sensing experiments conducted by NASA/LaRC. It is believed that anaerobic digestion may exert the most significant influence on sludge charactistics, which in turn would influence remote sensing response. For these reasons it is necessary to examine the theory behind the anaerobic digestion process and the changes it produces in significant sludge characteristics.

3.3.1. Anaerobic digestion process theory. - As described previously, the anaerobic digestion process is used as a stabilization step, its primary purposes being to cause a decrease in volatile and/or biodegradable organic content, destruction of pathogenic organisms, and production of methane gas. It is a suspended-growth biological process which is carried out in the complete absence of molecular oxygen, or under anaerobic conditions. By contrast, most biological wastewater treatment processes require oxygen and are termed aerobic processes. Under anaerobic conditions, the organic

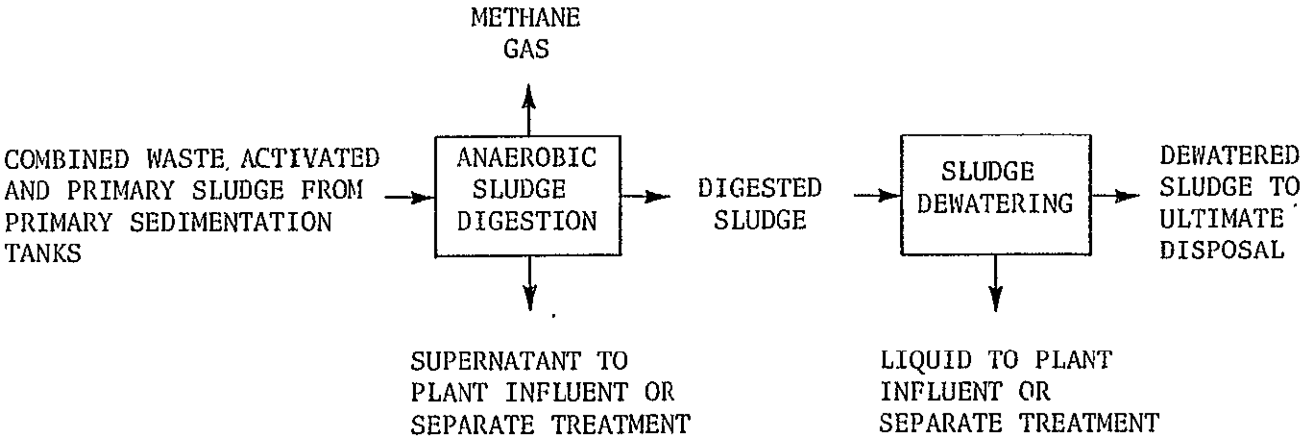

Figure 7. Typical sludge treatment flowsheet for combined sludge source.

materials in mixtures of primary and secondary sludges are biologically converted to methane ($CH_4$) and carbon dioxide ($CO_2$). The production and recovery of methane is an important factor which favors use of the anaerobic digestion process over other sludge stabilization methods. The methane gas produced has sufficient fuel value to support combustion, thus providing a means of energy recovery in the form of a readily usable fuel.

In order to understand how anaerobic digestion alters sludge characteristics, it is necessary to examine the process microbiology. Biological conversion of organic matter in raw sludges is thought to occur in two steps, which are illustrated in figure 8. These steps are differentiated by the types of bacteria which dominate the microbial population. In the first step, microorganisms hydrolyze and ferment complex organic compounds into simple organic acids, the most common of which are acetic and propionic acid. This group of microorganisms consists of facultative and obligate anaerobic bacteria, also identified collectively as "acid formers" (ref. 41).

In the second step, microorganisms convert the organic acids formed in the first stage to methane gas and carbon dioxide. The bacteria responsible for this conversion are strict anaerobes, and collectively they have been termed "methane formers" (ref. 41). It is in this second step that sludge stabilization is actually accomplished by the conversion of organic acids into methane and carbon dioxide. Methane gas is highly insoluble in water, and its departure from solution represents removal of organic carbon from the original carbon containing organic materials comprising sludge.

The methane-forming bacteria have very slow growth rates. The low growth yield signifies that only a small portion of the biodegradable organic material is being synthesized into new bacterial cells. This is in direct contrast to aerobic biological processes, such as activated sludge, where most of the organic matter in the influent wastewater is converted into new cell masses which must be wasted as secondary sludge. With the methane-forming bacteria, the majority of the organic matter entering the anaerobic digestion process is instead converted to methane gas, a useful end product.

Because of the low cellular growth rate and the conversion of organic matter to methane gas and carbon dioxide, sludge solids resulting from anaerobic

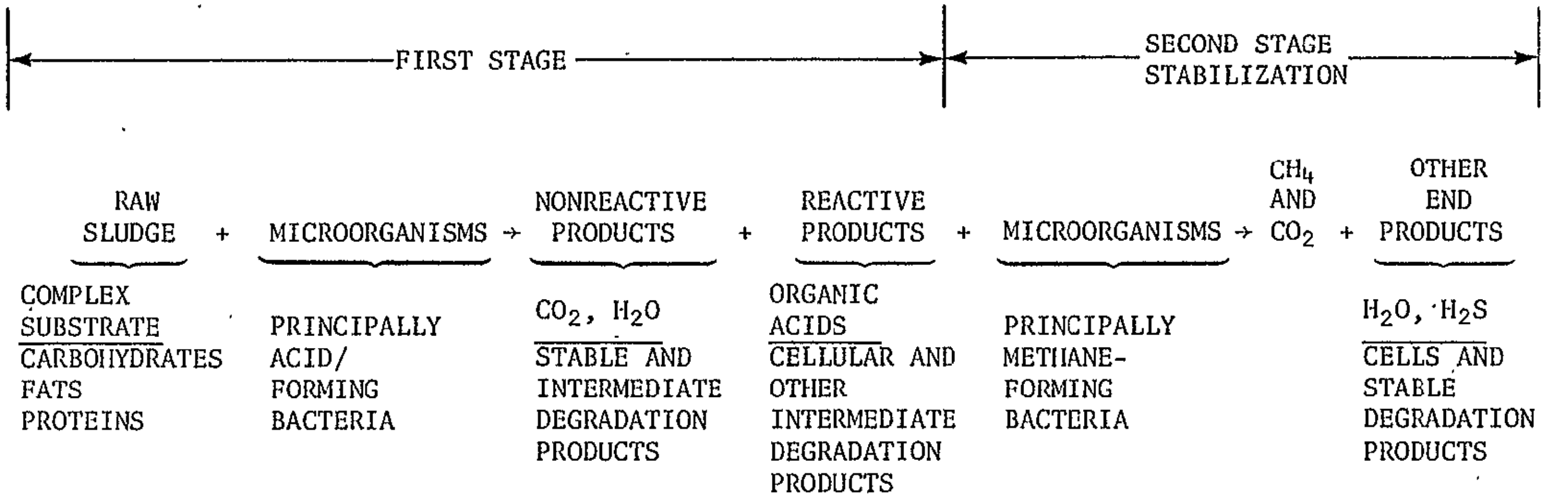

Figure 8. Biological steps in the anaerobic digestion process (refs. 41,

digestion are reasonably well stabilized. In this context a stabilized sludge is one which is unlikely to support biological activity which could result in undesirable changes in sludge characteristics, such as odor generation. After anaerobic digestion, dried or dewatered sludge solids are frequently suitable for disposal in sanitary landfills or on land as a soil conditioner without odor problems (ref. 42).

The physical configuration of a typical anaerobic digestion system for wastewater sludge stabilization is shown in figure 9. The first and second stages referred to in this figure are not related to the microbiological stages just described, but refer to the purpose of the two tanks used in a typical, continuous flow, anaerobic digestion system. The first stage employs a tank with complete mixing provided to aid uniform biological activity. The second stage tank is not provided with mixing devices. The primary function of the second tank is to separate the digested solids from the supernatant liquid, thus achieving some degree of solids concentration. It should also be noted that the first stage tank is equipped with a sludge heater, most commonly burning generated digester gas, so that the tank contents may be maintained at an elevated temperature. Because of the slow growth rate of anaerobic bacteria it is necessary to maintain an elevated temperature to maximize rate of growth if the process is to be completed within a reasonable detention time. Typical process sludge detention times range from 15 to 20 days (ref. 43).

5.3.2. Influence of anaerobic digestion on sludge characteristics. - The biological activity which characterizes the anaerobic digestion process results in significant alteration of sludge properties. Table 19 describes in general terms the characteristics of anaerobically digested sludge and also presents the characteristics of aerobically digested sludge for comparison. Aerobic digestion is another method of wastewater sludge stabilization, primarily used for waste/activated sludge since it is merely a long-term extension of the aeration period.

Table 20 quantifies many of the physical, chemical, and biological characteristics of a typical anaerobically digested sludge. This table also lists typical characteristics for raw (undigested) primary sludge to provide a basis of comparison. The characteristics of anaerobically digested sludge

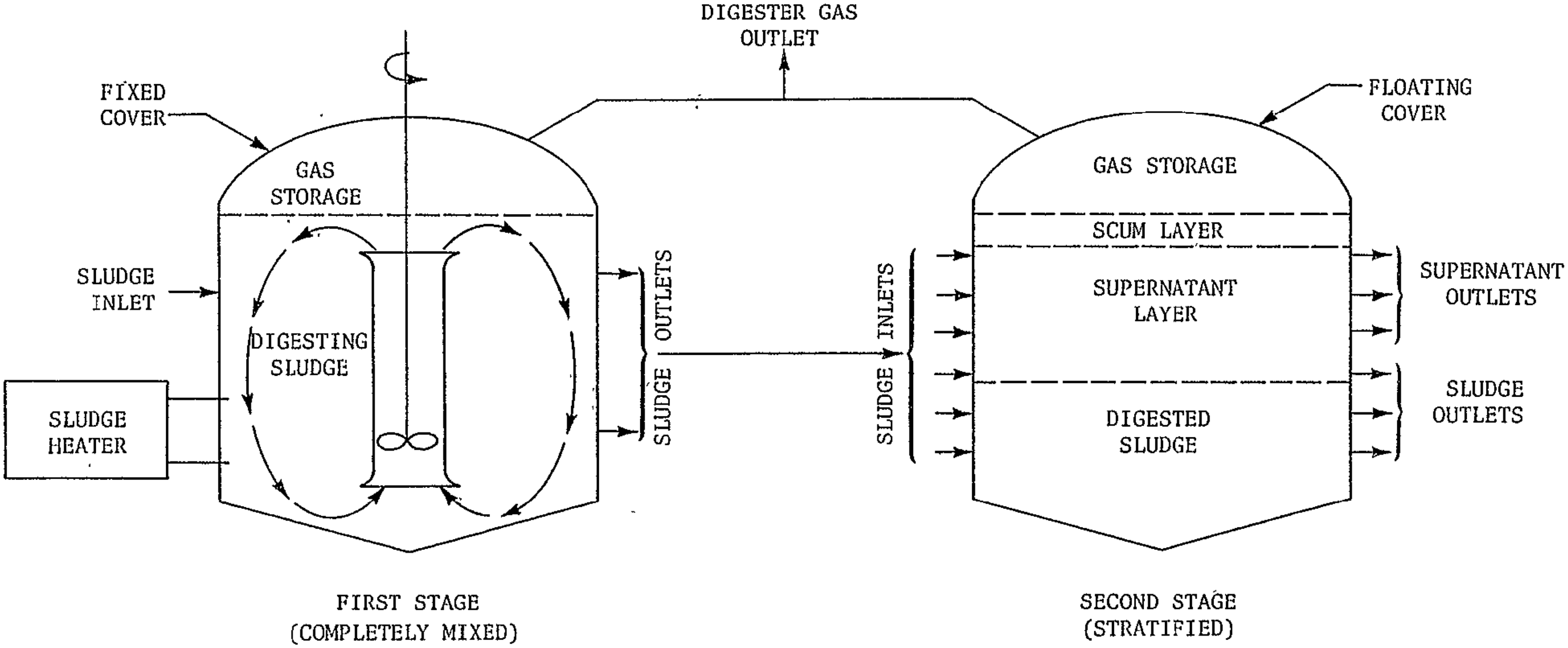

Figure 9. Typical anaerobic digestion system (ref. 13).

Table 19. General description of anaerobically and aerobically digested sludges (ref. 44).

| Sludge Type | Description |
|---|---|
| Anaerobically digested sludge | A thick slurry of dark brown to black particles that contains an exceptionally large quantity of entrained gases, principally carbon dioxide and methane. When thoroughly digested it is not offensive, its odor being relatively faint and like that of hot tar, burnt rubber, or sealing wax. When well digested it dewaters rapidly on sand drying beds, releasing an inoffensive odor resembling that of garden loam. Substantial additions of chemicals are needed to coagulate digested sludge prior to mechanical dewatering, owing to the finely divided nature of the solid particles. Dry residue is 30 to 60 percent volatile, and solids content of the digested sludge ranges from 6 to 12 percent by weight, depending on the mode of digester operation. |
| Aerobically digested sludge | A dark brown, flocculent, relatively inert sludge produced by long-term aeration of sludge. The suspension is bulky and difficult to thicken, thus creating problems of ultimate disposal. Since a clear supernatant cannot be decanted, the primary functions of an aerobic digester are stabilization of organics and temporary storage of waste sludge. The odor of aerobically digested sludge is not offensive, often being characterized as musty. |

Table 20. Typical characteristics of anaerobically digested sludge.

| Characteristic | Primary Sludge | Digested Sludge | | Ref. |
|---|---|---|---|---|
| | | Range | Typical | |
| Total dry solids (TS), % | 5.0 | 6.0-12.0 | 10.0 | (13) |
| Volatile solids (% of TS) | 65 | 30-60 | 40.0 | (13) |
| Grease and fats (ether soluble, % of TS) | 6-30 | 5-20 | -- | (13) |
| Protein (% of TS) | 25 | 15-20 | 18 | (13) |
| Nitrogen (N, % of TS) | 4.0 | 1.6-6.0 | 4.0 | (13) |
| Phosphorus ($P_2O_5$, % of TS) | 2.0 | 1.5-4.0 | 2.5 | (13) |
| Potash ($K_2O$, % of TS) | 0.4 | 0-3.0 | 1.0 | (13) |
| Cellulose (% of TS) | 10 | 8-15 | 10 | (13) |
| Iron (not as sulfide) | 2.5 | 3.0-8.0 | 4.0 | (13) |
| Silica ($SiO_2$, % of TS) | 15-20 | 10-20 | -- | (13) |
| pH | 6.0 | 6.5-7.5 | 7.0 | (13) |
| Alkalinity (mg/l as $CaCO_3$) | 600 | 2,500-3,500 | 3,000 | (13) |
| Organic acids (mg/l as HAc) | 500 | 100-600 | 200 | (13) |
| Thermal content (MJ/kg) | 16.5[a] | 6-14 | 9[b] | (13) |
| Specific gravity of sludge | 1.02 | - | 1.03 | (13) |
| Coefficient of compressibility | 0.87 | 0.70-0.86 | -- | (17) |
| Specific resistance ($sec^2/g \times 10^9$) | 10-30 | 3-30 | -- | (26) |
| Virus (PFU/100 ml) | 7.9 | - | 0.85 | (3) |
| Coliform ($10^6$/100 ml) | 11.4 | - | 0.4 | (3) |
| Salmonella (per 100 ml) | 460 | - | 29 | (3) |
| Pseudomonas (per 100 ml) | 46,000 | - | 34 | (3) |
| Arsenic (mg/l dry wt) | -- | 3-30 | 14 | (3) |
| Cadmium (mg/l dry wt) | -- | 5-2,000 | 15 | (3) |
| Chromium (mg/l dry wt) | -- | 50-30,000 | 1,000 | (3) |
| Copper (mg/l dry wt) | -- | 250-17,000 | 1,000 | (3) |
| Lead (mg/l dry wt) | -- | 136-7,600 | 1,500 | (3) |
| Mercury (mg/l dry wt) | -- | 3.4-18 | 6.9 | (3) |
| Nickel (mg/l dry wt) | -- | 25-8,000 | 200 | (3) |
| Selenium (mg/l dry wt) | -- | 1.7-8.7 | -- | (3) |
| Zinc (mg/l dry wt) | -- | 500-500,000 | 2,000 | (3) |
| Polychlorinated Biphenyls (mg/l dry wt) | -- | 1.2-105 | 3.2 | (3) |
| Chlordane (mg/l dry wt) | -- | 3-30 | -- | (3) |
| Dieldrin (mg/l dry wt) | -- | 0.3-2.2 | 0.16 | (3) |

[a] Based on 65 percent volatile matter.

[b] Based on 40 percent volatile matter.

will vary, of course, with the type of raw sludge fed to the digestion system. Sludge properties, including metals concentrations and persistent organic materials such as the pesticides chlordane and dieldrin, are a direct function of the wastewater source characteristics. The sources of these materials are usually industrial processes which contribute wastewater to the municipal treatment system. Therefore digested sludge metal and persistent organics concentrations are controlled by the amount and types of industrial wastewaters being processed. For this reason, comparison of sludge metals or trace organics concentrations is very difficult unless the sludge generation histories are fully known.

There are a number of significant changes in sludge properties resulting from anaerobic digestion which can be observed in table 20. Most important from the aspect of achieving sludge stabilization is the reduction of volatile solids and pathogenic organisms such as viruses, the coliform indicator group, Salmonella sp. and Pseudomonas sp.. Because of the hydrolysis of sludge solids and the release of bound water which occurs, an increase in total solids can also be achieved. Along with the decrease in volatile solids content, a corresponding decrease in the thermal content of the digested sludge will be observed. The majority of this loss in heating value is due to the release of methane gas, which has an approximate thermal content of 1.5 MJ/kg (ref. 17). Concentrations for nutrients such as nitrogen, phosphorus, and potassium are seen to remain constant or increase slightly. This is because the nutrients remain incorporated, or are converted into, bacterial cell mass and may be concentrated as the total solids level is increased. The chemical characteristic showing the most radical increase is alkalinity, expressed in equivalent amounts of calcium carbonate. This increase is caused by the release of carbonates, bicarbonates, and ammonia by methane-forming bacteria during the digestion process (ref. 43).

One of the most significant changes brought about by anaerobic digestion, especially with respect to properties which could potentially be monitored by remote sensing techniques, is the change in sludge particle size distribution. In general, the hydrolysis of organic materials by the acid-forming bacteria along with the completely mixed flow conditions result in a significant decrease in sludge particle size. Very little, if any, wastewater treatment plant operational data is available to support this statement. This is because sludge particle size analysis techniques, as discussed in section 2, are complex, difficult, and arbitrary in nature. The information such analyses might provide for process operation has not been viewed as justifying the considerable time and expense which would be necessary for routine measurement. A further complicating factor is that very few, if any, wastewater treatment plants monitor a significant number of characteristics for raw sludge entering the anaerobic digestion system. Normally only properties such as pH, total solids, and total volatile solids are measured for raw sludge. Therefore, even if particle size distribution data were available for digested sludges, one would have a difficult problem in finding similar data for raw sludges to provide a basis for comparison.

The evidence for decreasing particle size during anaerobic digestion has been indirectly gathered from measurements of the relative difficulty of dewatering sludges. In this regard the specific resistance to filtration test has been commonly applied. As mentioned in section 2, Bargmann et al. (ref. 36) found particle size along with compressibility to be the most important variables affecting filterability of digested sludges. Coackley and Allos (ref. 45) fractionated wastewater sludges into various size ranges and found that the specific resistance increased with decreasing particle size. Garber (refs. 46, 47) found that sludge anaerobically digested in the 49 to 57°C (thermophilic) range dewatered much more readily than sludge digested in the 30 to 38°C (mesophilic) range. This improvement in dewaterability was attributed to the fact that the thermophilic sludge contained fewer fines.

In a more recent article, Hansen et al. (ref. 48) discussed sludge dewatering problems at the joint water pollution control plant of the sanitation districts of Los Angeles County, California. A number of sludge-dewatering problems were explained by examining changes in anaerobically digested sludge properties produced by modifications of the wastewater treatment system over a six-year period. The primary change found was a shift in particle distribution, with an increased percentage of fine particles. Figure 10 illustrates the change in digested sludge particle size distribution over this six-year period.

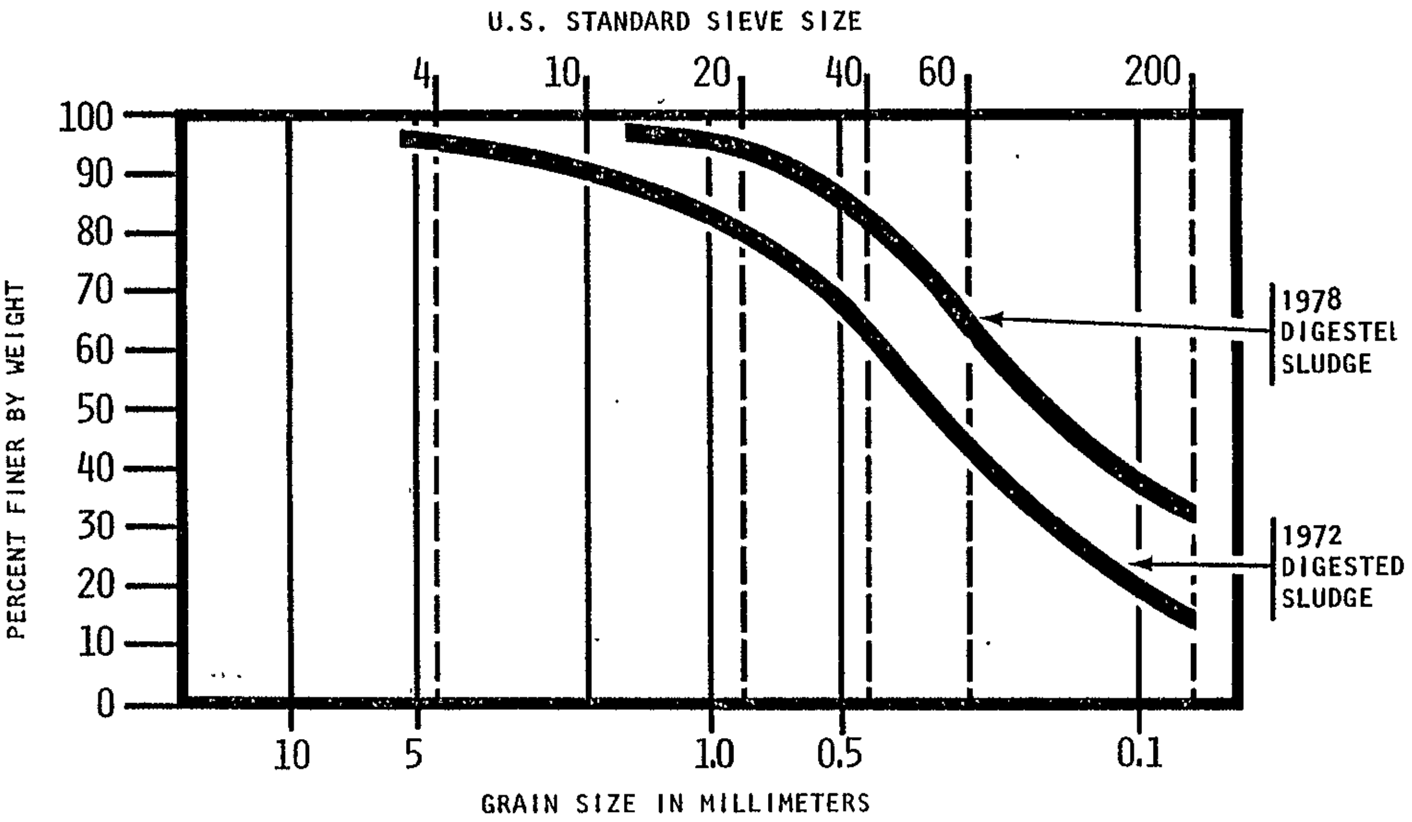

Figure 10. Particle size distribution of anaerobically digested sludge (ref. 48).

The most definitive research on the influence of anaerobic digestion on particle size distribution has been conducted by Karr (ref. 30). Using the particle sizing technique described in section 2, Karr obtained the average characteristics for anaerobically digested sludge shown in table 21. Also shown for comparative purposes are particle size and specific resistance values for primary and activated sludges. Capillary suction time, another measurement of the degree of difficulty encountered in sludge dewatering, is also listed with increasing values indicating increasing dewatering difficulty. Data on 6 samples of primary sludge, 13 samples of activated sludge, and 5 samples of anaerobically digested sludge were used to compute these averages. The values in table 21 indicate that anaerobically digested sludge showed the highest concentrations of supracolloidal, true colloidal, and dissolved solids, the three smallest particle size classifications. Corresponding to this higher relative concentration of small sludge particles was the highest average specific resistance and capillary suction time values, again illustrating the influence of particle size on dewaterability.

Table 21. Average particle size characteristics for anaerobically digested, primary, and activated sludges (ref. 30).

| Measurement | Anaerobically Digested Sludge | Primary Sludge | Activated Sludge |
|---|---|---|---|
| Specific resistance (m/kg × $10^{13}$) | 93.2 | 21.8 | 4.8 |
| Capillary suction time (sec) | 144 | 17 | 14 |
| pH | 7.3 | 5.8 | 6.0 |
| Solids (mg/l) | | | |
| Total | 10,266 | 9,698 | 8,841 |
| Rigid settleable | 3,374 | 6,452 | 1,920 |
| Fragile settleable | 4,054 | 2,320 | 6,587 |
| Supracolloidal | 1,997 | 355 | 84 |
| True colloidal | 301 | 45 | 7 |
| Dissolved | 540 | 526 | 243 |

Further illustration of the effect of anaerobic digestion on particle size distribution can be made by examing the data presented in table 22. In this experiment Karr (ref. 30) anaerobically digested primary sludge on a laboratory scale and determined the change in particle size distribution

Table 22. Effect of anaerobic digestion of primary sludge on particle size distribution and dewaterability (ref. 30).

| Measurement | Raw Primary Sludge | Digested Primary Sludge |
|---|---|---|
| Specific resistance (m/kg × $10^{13}$) | 18.2 | 112 |
| Capillary suction time (sec) | 42 | 246 |
| Total volatile solids (% of total solids) | 73 | 60 |
| Solids (mg/l) | | |
| Total | 21,052 | 7,504 |
| Rigid settleable | 15,426 | 1,694 |
| Fragile settleable | 4,590 | 3,310 |
| Supracolloidal | 528 | 1,810 |
| True colloidal | 22 | 242 |
| Dissolved | 486 | 448 |

and dewaterability. Again it can be noted that the concentrations of supracolloidal and true colloidal solids increased drastically, with an accompanying increase in specific resistance and capillary suction time values (decrease in dewaterability).

In summary, it can be stated that the anaerobic digestion process for sludge stabilization brings about many significant changes in sludge characteristics. These changes are a result of both the biological-biochemical reactions involved and the physical operating conditions (complete mixing, elevated temperature, relatively long solids detention time) utilized. With respect to the objectives of this study, these conclusions are most important because they demonstrate that primary and secondary sludges can lose their identifying or unique properties if subjected to anaerobic digestion. Thus if remote sensing of an ultimate disposal technique such as ocean dumping is attempted, the observed sludge characteristics will be greatly altered if the sludge has undergone prior anaerobic digestion.

# 4. SLUDGE MANAGEMENT: CITY OF PHILADELPHIA

Within the scope of this study, sludges generated by the City of Philadelphia require special attention because of the coverage their ocean disposal has received during NASA/LaRC remote sensing experiments. The following presentation is intended to define the City of Philadelphia's wastewater treatment plants which have been involved in remote sensing experiments, and to establish the types of sludge generated, sludge treatment and disposal methods used, and sludge characteristics observed. Section 4.4 then attempts to relate this information to interpretation of remote sensing experiments.

## 4.1. City of Philadelphia Wastewater Treatment Plants

The City of Philadelphia owns and operates three wastewater treatment facilities with a combined capacity of 465 million gallons per day (465 gal × $10^6$/d or 176 × $10^4$ $m^3$/d). Flow is collected from a service area covering over 360 sq. mi (9.3 × $10^8$ $m^3$) in the Philadelphia metropolitan area (ref. 4). The three facilities are the Northeast, Southwest, and Southeast Water Pollution Control Plants (ref. 49).

4.1.1. Northeast Water Pollution Control Plant. - This wastewater treatment plant employs grit removal, primary sedimentation, and intermediate activated sludge secondary treatment. An intermediate type activated sludge system is one in which the organic loading rate is higher and the organic removal efficiency lower than for a conventional activated sludge process. Plant capacity in 1977 was 190 gal × $10^6$/d (7.2 × $10^5$ $m^3$/d), serving a population of 1.2 million. Approximately 6 percent of the wastewater volume and 21 percent of the 5-day 20°C biochemical oxygen demand (BOD) load are contributed by industrial sources. Industries in the Northeast Plant drainage area include organic chemical production, animal waste rendering, automobile parts manufacturing, paper recycling, and food processing (ref. 50).

Figure 11 presents a process flow diagram for the existing Northeast Plant, including sludge treatment units which will be discussed in a later section. In fiscal year 1977 this treatment system attained removals of

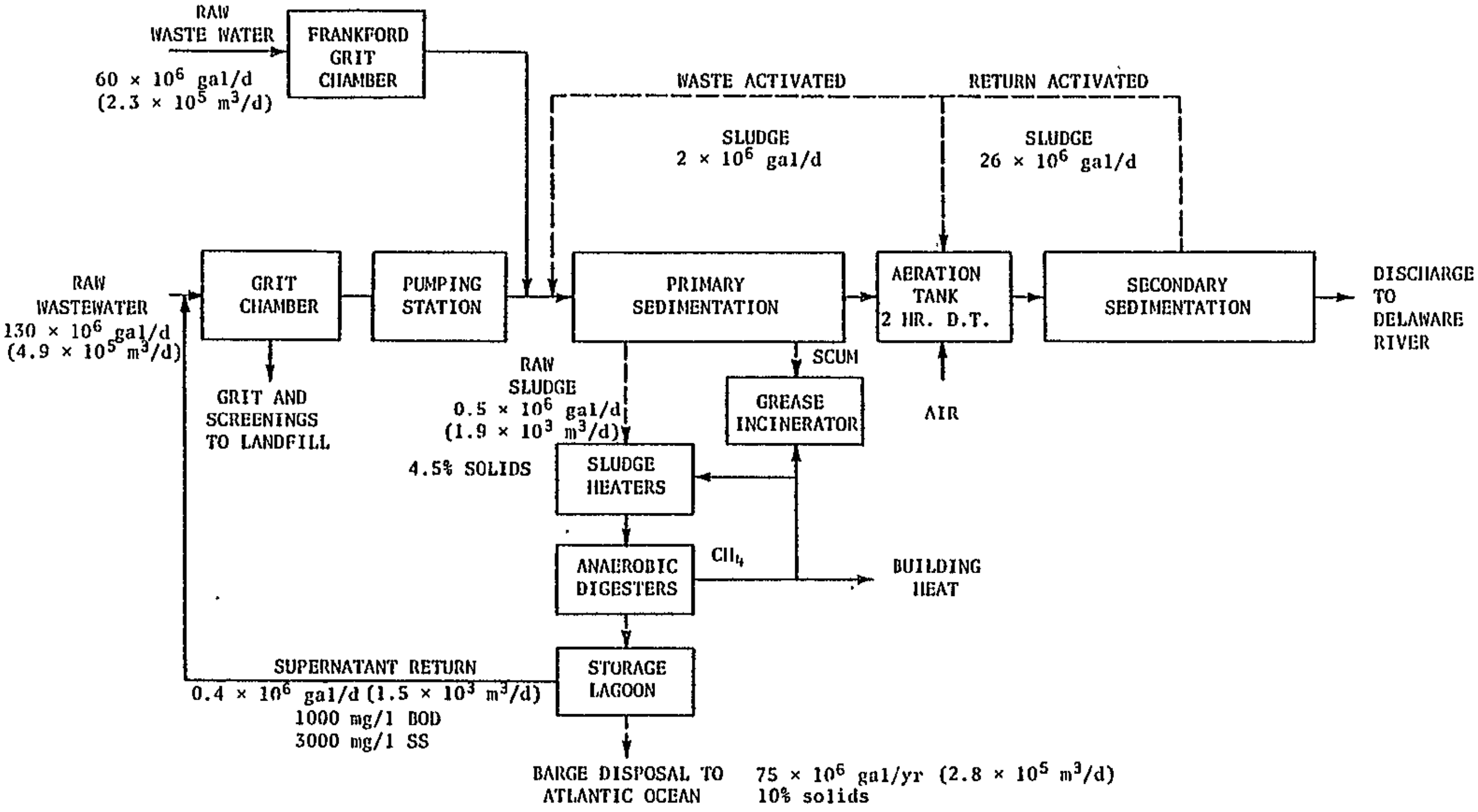

Figure 11. Northeast Water Pollution Control Plant process flowsheet (ref. 50).

5-day 20°C BOD and suspended solids (SS) of 58.4 and 71.3 percent respectively at an average flow of 180.7 million gal ($6.8 \times 10^5$ $m^3$)/d (ref. 51). Planned plant expansion and upgrading to full secondary treatment will add additional primary sedimentation and pure oxygen activated sludge facilities to reach a capacity of 250 million gal ($9.46 \times 10^5$ $m^3$)/d, and reductions of 92 percent BOD and SS (ref. 50).

Inspection of figure 11 reveals a number of important facts concerning sludge generation. Since both primary sedimentation and activated sludge secondary treatment are utilized, both primary and biological sludges are generated. But, excess activated sludge is not wasted separately to sludge treatment and disposal processes. Instead it is wasted to the primary sedimentation tanks for removal. Therefore the Northeast Plant generates a combined primary-waste activated sludge for subsequent treatment and disposal. This point is significant with respect to remote sensing experiments which have attempted to make a differentiation between primary and secondary sludges from this plant.

4.1.2. Southwest Water Pollution Control Plant. - This wastewater treatment plant is a primary treatment system, employing grit removal and air flocculation for increased oil, grease, and suspended solids removals during primary sedimentation. Plant capacity in 1977 was 136 million gal ($5.1 \times 10^5$ $m^3$)/d, serving a drainage area of 51,600 acres ($2.09 \times 10^6$ $m^2$) (ref. 52).

Figure 12 presents a process flow diagram for the existing Southwest Plant. In fiscal year 1977 this treatment system attained removals of 5-day 20°C BOD and SS of 31 and 51 percent respectively at an average flow of 171.35 million gal ($6.49 \times 10^5$ $m^3$/d) (ref. 53). Planned expansion will upgrade the Southwest Plant to full secondary treatment at a daily average flow of 210 million gal ($7.95 \times 10^5$ $m^3$)/d. Again the pure oxygen activated sludge process will be used to provide secondary treatment.

From figure 12 it can be seen that the Southwest Plant generates only primary sludge. In addition, primary sludge from the Southwest Plant is pumped to the Southwest Plant for subsequent treatment and disposal.

4.1.3. Southeast Water Pollution Control Plant. - The Southeast Plant is identical in its liquid process flow scheme to the Southwest Plant. It is

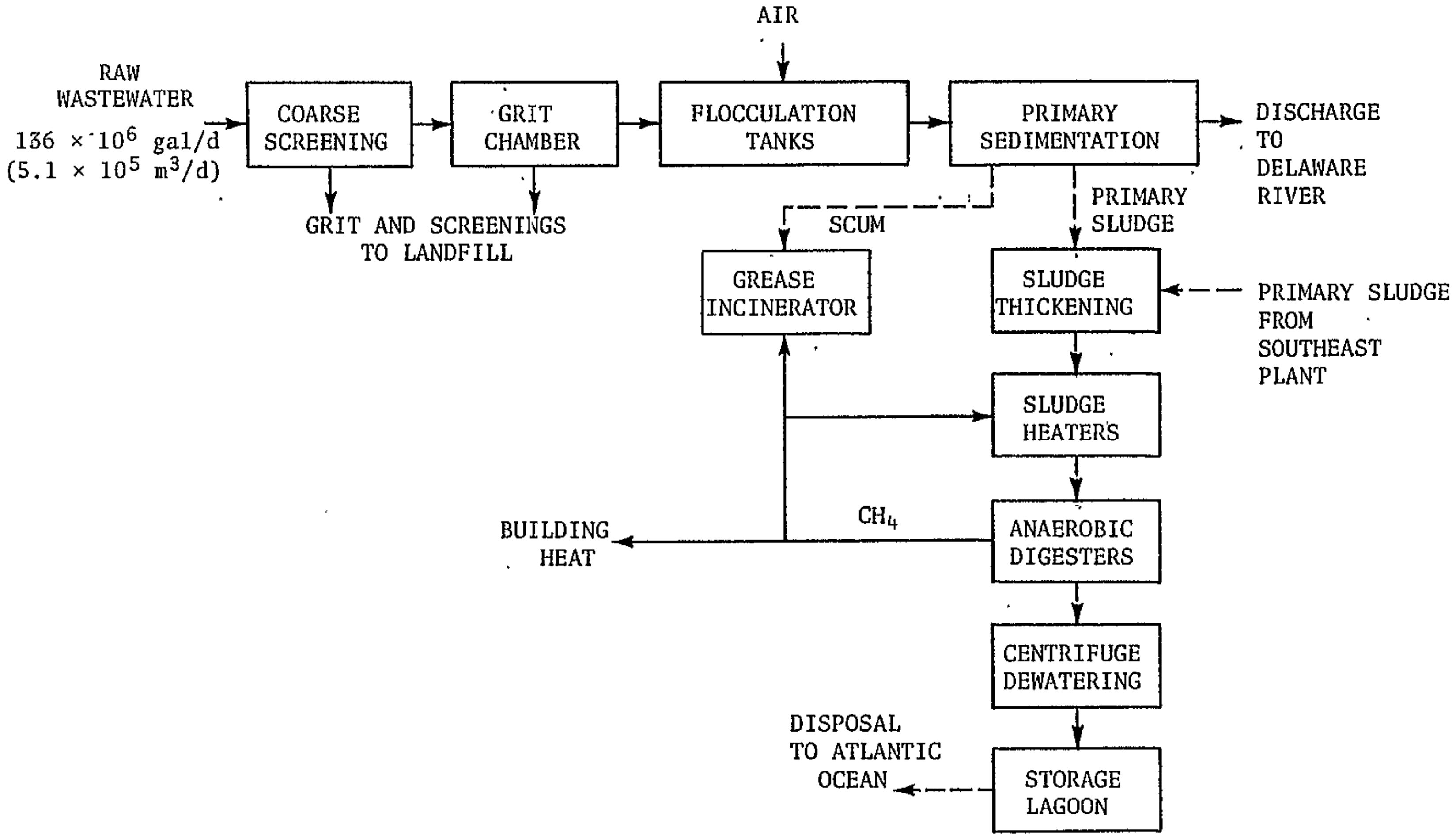

Figure 12. Southwest Water Pollution Control Plant process flowsheet (ref. 52).

a primary treatment plant rated for a wastewater flow of 136 million gal ($5.1 \times 10^5$ $m^3$)/d. The treatment process makes use of coarse screening, grit removal, and air flocculation to increase oil, grease, and suspended solids removal in primary sedimentation tanks which follow. Like the Southwest Plant, scum is skimmed from the primary sedimentation tanks and burned in a grease incinerator (ref. 54). The major difference between the two primary wastewater treatment plants is that the Southeast Plant has no sludge treatment facilities of its own (ref. 49). All of the primary sludge generated is pumped from a 23,000-gal (87-$m^3$) holding tank through a 4.7-mi ($7.6 \times 10^3$ m), 8-in. (20.3-cm) diameter force main to the Southwest Plant for thickening, anaerobic digestion, dewatering, and ultimate disposal.

The Southeast Plant services an area encompassing 20.7 sq mi ($5.4 \times 10^7$ $m^2$) and serving almost 500,000 people (ref. 54). The drainage area for this plant includes many of the high density sections of Philadelphia, including the center city business district and many of its historical sights. There are also a considerable number of industrial wastewater discharges in the area served, amounting to 14 million gal ($5.3 \times 10^4$ $m^3$)/d or 12 percent of the total plant flow. Many of the industries produce food products such as sugar and alcoholic beverages, and therefore discharge waste water high in soluble 5-day 20°C BOD.

In fiscal year 1975 the Southeast Plant received an average wastewater flow of 118.7 million gal ($4.5 \times 10^5$ $m^3$)/d and removed 59 percent of the influent suspended solids and 50 percent of the influent 5-day 20°C BOD (ref. 55). It is planned that the plant will be upgraded to full secondary treatment utilizing the pure-oxygen activated sludge process to achieve at least 90 percent removal of BOD and SS. The upgraded secondary treatment facility will retain a hydraulic capacity of 136 million gal ($5.1 \times 10^5$ $m^3$)/d and will continue to pump primary sludge, plus a new waste activated sludge stream, to the Southwest Plant for subsequent processing and disposal (ref. 54).

### 4.2. Sludge-Processing Facilities

Although the City of Philadelphia has three wastewater treatment plants, combination of the southwest and southeast primary sludge flows reduces the sludge treatment systems to two. The Northeast Plant in fiscal 1977 generated 546,000 gal (2.1 × $10^3$ $m^3$) of mixed primary and waste activated sludge per day, with an average total solids concentration of 4.31 percent (ref. 51). The Southwest and Southeast Plants generated 420,000 gal (1.6 × $10^3$ $m^3$) per day of primary sludge with an average total solids concentration of 4.20 percent (ref. 53).

4.2.1. Sludge processing - Northeast Plant. - Mixed primary-waste activated sludge is removed from the primary sedimentation tanks and pumped to sludge heaters. Through submerged combustion of a digester gas-air mixture the sludge temperature is raised to 105°F (40.5°C). Heated sludge is then pumped to 8 circular anaerobic digestion tanks, each 110 ft (33.5 m) in diameter and 35 ft (10.7 m) deep. Sludge is retained in the anaerobic digestion process for 28 days before it is withdrawn and pumped to a 10-acre (40,469-$m^2$), 9-ft (2.7-m) deep storage lagoon. In fiscal 1977 the anaerobic digestion system achieved an average volatile solids reduction of 52 percent (ref. 51).

In the sludge storage lagoon, anaerobic digester supernatant enters containing approximately 2 percent total solids. Lagoon overflow liquid, containing approximately 0.3 percent total solids, is recycled to the influent of the wastewater treatment system. In the lagoon some sludge thickening occurs and sludge averaging from 10 to 12 percent total solids is pumped by dredge to sludge disposal barges. Each barge holds about 1.8 million gal (6.8 × $10^3$ $m^3$) of sludge, and approximately 75 barge trips to an ocean disposal site off the Atlantic Coast are made each year. A significant point is that most barge loads have only one-half the barge volume made up of sludge from the Northeast Water Pollution Control Plant. The remaining half of the barge volume is filled with sludge from the joint processing facilities at the Southwest Water Pollution Control Plant (ref. 50).

Up until 1961 all digested sludge was stored in lagoons. Ocean disposal of sludge began in 1961 when it became apparent that, due to growth in the drainage area, available lagoon space would not be sufficient. Between 1961 and 1974, Philadelphia barged approximately 960 million gal ($3.5 \times 10^6$ $m^3$) of sludge to the ocean (ref. 56).

4.2.2. Sludge processing - Southwest Plant - Primary sludges generated by the Southwest and Southeast Plants are first concentrated in gravity thickeners and then pumped to sludge heaters. Submerged combustion of digester gas then heats the sludge before it is pumped to eight anaerobic digestors, similar in design to those used at the Northeast Plant. Digested sludge is then centrifugally thickened before being loaded on a barge for disposal, or is pumped to a sludge storage lagoon for thickening. In the latter case lagooned sludge is eventually dredged and pumped to ocean disposal barges (ref. 53).

In summary, all sludges produced by the three City of Philadelphia wastewater treatment facilities are anaerobically digested. The digested sludges are then either centrifugally or lagoon thickened, pumped to a barge, and disposed of by ocean dumping. In the majority of trips, sludges from all three plants are mixed together in any one barge load. The three plants produce one million gal (3785 $m^3$) of anaerobically digested sludge per day, or approximately 190 tons ($1.7 \times 10^5$ kg) per day of dry sludge solids (ref. 60).

### 4.3. Sludge Characteristics

Characteristics of the wastewater sludges generated by Philadelphia's three treatment facilities were obtained from a number of sources. The most direct source was the City of Philadelphia Water Department, which is responsible for treatment system operation. Mr. William Wankoff, P.E., Chief of the Wastewater Treatment Section, was visited in October 1977 in Philadelphia to acquire the needed data. Later information was obtained through correspondence with Mr. Wankoff. An indirect source of sludge characteristic information was the U. S. Environmental Protection Agency Region III office in Philadelphia. Mr. William Muir of this office was able to supply data which had been submitted as part of the ocean disposal permit program.

Ideally it would be helpful to have information describing the characteristics of raw sludge, digested sludge, and sludge barged for ocean disposal. Unfortunately, little information is available concerning raw and digested sludge which could be used to examine the influence of the anaerobic digestion process on sludge characteristics which are significant during ocean disposal. This is a result of the fact that relatively little sludge characteristics data is required to monitor routine plant operation, including the anaerobic digestion process. Analysis of additional characteristics cannot be justified from the standpoint of benefiting process operation, when the time and expense are considered. The majority of available sludge characteristics information exists for barged sludge which is ocean disposed. This is a direct result of EPA ocean disposal permits criteria which require routine monitoring of a large number of parameters.

The available raw and digested sludge characteristics for Philadelphia sludges are shown in tables 23 and 24. As can be observed from these tables, relatively few parameters are monitored for these sludge types.

Table 23. Raw and anaerobically digested sludge characteristics for the Northeast Plant (ref. 51).

| Characteristic | Raw Sludge<br>Fiscal 1975 | Raw Sludge<br>Fiscal 1976 | Raw Sludge<br>Fiscal 1977 | Digested Sludge<br>Fiscal 1975 | Digested Sludge<br>Fiscal 1976 | Digested Sludge<br>Fiscal 1977 |
|---|---|---|---|---|---|---|
| pH | 5.9 | 7.4 | 6.5 | 7.0 | 7.0 | 6.8 |
| Total solids (TS, %) | 4.6 | 4.6 | 4.31 | 7.5 | 8.1 | 8.0 |
| Volatile solids (% of TS) | 67.1 | 67.4 | 66.33 | 50.2 | 49.8 | 54.00 |
| Alkalinity (mg/l as $CaCO_3$) | -- | -- | -- | 1953 | 2567 | 2647 |
| Volatile acids (mg/l as HAc) | -- | -- | -- | 895 | 1388 | 1063 |

Table 24. Raw and anaerobically digested sludge characteristics for the Southwest Plant (ref. 53).

| | Raw Sludge | | | Digested Sludge | | |
|---|---|---|---|---|---|---|
| Characteristic | Fiscal 1975 | Fiscal 1976 | Fiscal 1977 | Fiscal 1975 | Fiscal 1976 | Fiscal 1977 |
| pH | 6.0 | 5.9 | 6.0 | 6.9 | 6.7 | 5.9 |
| Total solids (TS, %) | 5.0 | 4.7 | 4.2 | 5.7 | 5.8 | 5.9 |
| Volatile solids (% of TS) | 58 | 63 | 64 | 43 | 48 | 46.5 |
| Alkalinity (mg/l as CaCO ) | -- | -- | -- | 1526 | 1585 | 1719 |
| Volatile acids (mg/l as HAc) | -- | -- | -- | 433 | 1592 | 2277 |

Tables 25, 26, and 27 present mean characteristics for anaerobically digested, lagooned, and barged sludges from the Northeast and Southwest Water Pollution Control Plants for the years 1975, 1976, and 1977. Samples for these analyses were taken as sludge was pumped into barges for later transport and ocean disposal, in accordance with EPA Ocean Dumping Regulations and Criteria (ref. 57). The values given for 1977 represent sludge barged only from January through June, as later data was not available. The 1976 data also include combined sludge values, representing characteristics of barge contents after Northeast Plant and Southwest Plant sludges had been mixed to make one full load (ref. 49).

The barged sludge data sheets used to compute the average values shown in table 27 were also interesting because they recorded the percentage of each barge load made up by Northeast Plant and Southwest Plant sludges. For the 29 barge loads for which data was provided, total barge volume averaged 48.4 percent Northeast Plant sludge and 51.6 percent Southwest Plant sludge (ref. 59). This agrees with the rough estimates discussed earlier in this chapter when sludge processing steps were described. However, six barge loads contained entirely sludge from the Northeast Plant, while five contained only sludge from the Southwest Plant. There was considerable variation about the mean values given above. From these figures it can be concluded that on any

Table 25. Barged sludge characteristics—1975 (ref. 58).

| Characteristic | Northeast Plant Sludge | Southwest Plant Sludge |
|---|---|---|
| Total solids (TS, %) | 12.53 | 5.10 |
| Volatile solids (% of TS) | 49.24 | 43.28 |
| Chemical oxygen demand (COD, g/kg) | 129.2 | 42.9 |
| Total kjeldahl nitrogen (TKN, g/kg) | 20.4 | 25.3 |
| Nitrate nitrogen ($NO_3$, mg/l × $10^{-3}$) | 1.25 | 2.5 |
| Orthophosphate phosphorus ($PO_4$, g/kg) | 8.7 | 7.1 |
| Hexane extractable oil and grease (g/kg) | 131.3 | 54.8 |
| Mercury | | |
| Solid (mg/kg) | 2.17 | 2.73 |
| Liquid (μg/l) | 7.23 | 15.2 |
| Cadmium | | |
| Solid (mg/kg) | 108.3 | 31.4 |
| Liquid (μg/l) | 23.34 | 24.8 |
| Lead (mg/kg) | 2,272 | 1,544 |
| Copper (mg/kg) | 1,613 | 825 |
| Iron (mg/kg) | 9,823 | 8,644 |
| Zinc (mg/kg) | 5,391 | 3,043 |
| Manganese (mg/kg) | 2,119 | 590 |
| Chromium (mg/kg) | 1,459 | 1,240 |
| Nickel (mg/kg) | 391 | 100 |
| Bioassay (mg/l) | 11,928 | 32,566 |

Table 26. Barged sludge characteristics—1976 (ref. 49).

| Characteristic | Northeast Plant Sludge | Southwest Plant Sludge | Combined Sludge |
|---|---|---|---|
| Total solids (TS, %) | 11.8 | 6.16 | 9.1 |
| Volatile solids (% of TS) | 49.7 | 46.5 | 50.5 |
| Oil and grease (g/kg) | 95.7 | 62.0 | 63.3 |
| Phenols (mg/l) | 5.8 | 1.55 | 3.5 |
| Chemical oxygen demand (COD, g/kg) | 120.8 | 53.6 | 79.9 |
| Total kjeldahl nitrogen (TKN, g/kg) | 16.8 | 15.3 | 15.0 |
| Orthophosphate phosphorus ($PO_4$, g/kg) | 8.9 | 8.2 | 9.5 |
| Nitrate nitrogen ($NO_3$, mg/l) | 0 | 0 | 0 |
| Fecal coliform (organisms/100 ml × $10^4$) | 7.9 | 1.4 | 6.5 |
| Total coliform (organisms/100 ml × $10^5$) | 8.3 | 16.3 | 9.9 |
| Mercury | | | |
| Solid (mg/kg) | 3.1(1.9)[a] | 2.8(3.6)[a] | 2.4 |
| Liquid (μg/l) | 0.02 | 0.02 | 0.01 |
| Cadmium | | | |
| Solid (mg/kg) | 74.6(57)[a] | 27.3(22)[a] | 43 |
| Liquid (mg/l) | 0.01 | 0.01 | 0.02 |
| Chromium (mg/kg) | 1,653 | 787 | 1,137 |
| Copper (mg/kg) | 2,545 | 1,341 | 1,789 |
| Iron (mg/kg) | 18,687 | 17,969 | 16,508 |
| Lead (mg/kg) | 2,165 | 2,024 | 2,320 |
| Manganese (mg/kg) | 3,205 | 503 | 2,075 |
| Nickel (mg/kg) | 438 | 98 | 250 |
| Zinc (mg/kg) | 6,998 | 3,084 | 5,381 |
| Polychlorinated biphenyls (mg/l) | 0.74 | 0.51 | 0.87 |
| Aldrin (mg/l) | 0.02 | 0.02 | 0.03 |
| Petroleum hydrocarbons (mg/l) | 7,633 | 4,198 | 5,987 |
| Bioassay (mg/l) | -- | -- | 839 |

[a] Values in parentheses from independent laboratory.

Table 27. Barged sludge characteristics—1977 (ref. 59).

| Characteristic | Northeast Plant Sludge | Southwest Plant Sludge |
|---|---|---|
| Total solids (TS, %) | 13.5 | 6.8 |
| Volatile solids (% of TS) | 51 | 51 |
| Oil and grease (g/kg) | 81.3 | 61.4 |
| Phenols (mg/l) | 7.0 | 2.40 |
| Chemical oxygen demand (COD, g/kg) | 118.1 | 69 |
| Total kjeldahl nitrogen (TKN, g/kg) | 17.6 | 15.3 |
| Orthophosphate phosphorus ($PO_4$, g/kg) | 10.8 | 8.91 |
| Nitrate nitrogen ($NO_3$, mg/l) | 0.00 | 0.00 |
| Fecal coliform (organisms/100 ml × $10^4$) | 18.0 | 8.75 |
| Total coliform (organisms/100 ml × $10^5$) | 30.7 | 10.9 |
| Mercury | | |
| Solid (mg/kg) | 2.94 | 2.88 |
| Liquid (μg/l) | 28.62 | 24.76 |
| Cadmium | | |
| Solid (mg/kg) | 73 | 31 |
| Liquid (mg/l) | 0.0083 | 0.0102 |
| Chromium (mg/kg) | 1,963 | 738 |
| Copper (mg/kg) | 1,850 | 791 |
| Iron (mg/kg) | 20,525 | 15,900 |
| Lead (mg/kg) | 2,253 | 2,330 |
| Manganese (mg/kg) | 2,730 | 403 |
| Nickel (mg/kg) | 323 | 88 |
| Zinc (mg/kg) | 7,228 | 3,898 |

given day it would be difficult, if not impossible, to assume the exact source of sludge undergoing ocean disposal.

Comparison of the Philadelphia sludge characteristics shown in tables 25, 26, and 27 with characteristics for other east coast municipal wastewater sludges undergoing ocean disposal will be mainly carried out in section 5. However, at this time it would be beneficial to compare metals concentrations of the Philadelphia sludges to concentrations observed in other municipal sludges generated in the United States. It must be remembered that sludge metal concentrations are difficult to interpret meaningfully, since they are a direct function of the magnitude and character of industrial discharges. Table

28 presents such a comparison of heavy metal concentrations. "Philorganic" is a dewatered (60 to 70 percent total solids) sludge which has been excavated from the older City of Philadelphia sludge storage lagoons at the Southwest Plant. It is being given away to the general public as a free soil conditioner in an attempt to empty extra sludge storage lagoons so that the land may be used for plant expansions (ref. 60).

Comparisons of the heavy metals concentrations tabulated in table 28 indicate that the metal analysis of Philadelphia sludge is comparable to that of other large cities in the United States. As can also be observed from tables 25, 26, and 27, the Southwest Plant sludge has consistently lower values than sludge from the Northeast Plant. This relationship is due to the differences in industrial sources discharging to the two wastewater treatment facilities.

## 4.4. Relevance to Remote Sensing Experiments

The information which has been presented describing City of Philadelphia wastewater treatment facilities, sludge-processing techniques, and sludge characteristics was developed with a distinct purpose. Such information directly relates to the interpretation of remote sensing data taken during experiments monitoring the ocean disposal of Philadelphia's sludges.

4.4.1. Differentiation between primary and secondary sludges. - One clear point to be recognized is that there is not a true secondary or biological sludge stream generated by the City of Philadelphia. At present the Northeast Plant is the only facility employing secondary treatment. While excess activated sludge is generated, it is recycled to the primary sedimentation tanks for wasting. Therefore, the Northeast Plant generates a mixed primary-secondary sludge with a unique set of properties. It is not correct to assume that sludge disposed from this plant is secondary sludge.

The problem just described is avoided at the Southwest Plant, since only primary sludge is generated by the Southwest and Southeast Plants. Thus, one might conclude that sludge taken for disposal from the Southwest sludge-processing facilities would be representative of a municipal primary sludge. The complicating variable is that in the majority of barge loads transported for

Table 28. Heavy metal comparison—Philadelphia vs. other United States cities—July 1976 (ref. 60).

| City | Zinc (mg/kg) | Cadmium (mg/kg) | Cd:Zn | Copper (mg/kg) | Nickel (mg/kg) | Lead (mg/kg) | Chromium (mg/kg) |
|---|---|---|---|---|---|---|---|
| Philadelphia | | | | | | | |
| Northeast | 5,386 | 105 | 1.94 | 1,173 | 3.5 | 2,412 | 1,146 |
| Southwest | 2,031 | 33 | 1.6 | 699 | 148 | 1,261 | 712 |
| Philorganic | 1,744 | 22 | 1.3 | 536 | 89 | 1,069 | 592 |
| Chicago-Calumet | 6,100 | 209 | 3.4 | 1,235 | 21 | 1,686 | 984 |
| New York City (Aug.) | 2,550 | 28 | 1.1 | 2,300 | 340 | 4,500 | 1,640 |
| New Jersey (Aug.) | 3,300 | 132 | 4.0 | 840 | 173 | 1,620 | 1,300 |
| Washington, D.C. | 1,908 | 18 | 1.0 | 583 | 79 | 634 | -- |
| Camden, N.J. | 1,839 | 41 | 2.2 | 379 | 67 | 563 | 402 |
| Denver, CO | 3,100 | 53 | 1.7 | 1,600 | 403 | 1,083 | 690 |
| San Francisco, CA | 4,700 | 40 | 0.85 | 730 | 270 | 1,000 | 1,600 |
| Milwaukee, WI | 1,262 | 79 | 6.2 | 359 | 83 | 710 | -- |

ocean disposal, Southwest Plant primary sludge is mixed with varying percentages of combined primary-secondary sludge from the Northeast Plant. Therefore, in a majority of cases, the sludge undergoing ocean disposal is a mixture of primary and secondary sludge. It would not be representative of a typical municipal primary sludge. If a barge were monitored which contained only Southwest Plant sludge, there is yet another complicating variable which blocks simple generalization of sludge type. This variable is the subject of the next discussion.

4.4.2. Influence of Anaerobic Digestion. - As stated previously, all sludges generated by the City of Philadelphia receive anaerobic digestion before being ocean disposed. Section 3 firmly established that the anaerobic digestion process significantly alters properties of raw sludge. Therefore, primary sludge generated by the Southeast and Southwest Plants is converted to anaerobically digested primary sludge. Expanding on this principle, it can be stated that the City of Philadelphia does not dispose of primary or secondary sludge. It disposes of anaerobically digested primary and anaerobically digested primary-secondary sludges. The anaerobic digestion process acts as a giant homogenization step which begins with sludges of distinct characteristics and produces a blended anaerobically digested sludge.

In summary, classification of observed Philadelphia sludge disposal operations into primary and secondary sludge types is an attempt to impose artificial and incorrect differentiation on the actual situation. If ocean sludge disposal operations were observed in which barges containing only Southwest Plant sludge or only Northeast Plant sludge were monitored, then the correct differentiation would be to say that one represented an anaerobically digested primary sludge, and the second represented an anaerobically digested primary-secondary sludge. However, the anaerobic digestion process would tend to eliminate any observable differences in sludge characteristics.

## 5. CHARACTERISTICS OF OTHER EAST COAST SLUDGES

In order to attain the objectives of this study, it was necessary to determine if sludges generated by the City of Philadelphia were representative of other municipal sludges generated by east coast cities and receiving ocean disposal. To answer this question, it was necessary to gather sludge characteristics data describing these other east coast sludges.

This task was undertaken by contacting the Region II Office of the EPA, which serves the New York and New Jersey metropolitan areas. These areas have the only wastewater treatment systems, other than Philadelphia, which are still practicing ocean sludge disposal on the east coast.

Required information detailing characteristics of municipal sludges in EPA Region II undergoing ocean disposal was obtained from the ocean disposal permit records. Mr. Robert M. Cibulskis and Dr. Peter W. Anderson of the Region II EPA Office in Edison, New Jersey were most helpful in supplying the required data. Approximately 200 pages of sludge characteristics data for 13 different ocean disposal permits, all in New York or New Jersey, were analyzed.

Tables 29, 30, and 31 summarize sludge characteristics contained in the permit records for 1975, 1976 and 1977. Mean values, values of the range, and the number of samples analyzed are tabulated.

Comparison of the sludge characteristics just described with the characteristics for Philadelphia's sludges shown in tables 25, 26, and 27 reveals that Philadelphia's sludges are similar to the New York-New Jersey sludges. This statement is made with consideration given to the large variability of the characteristics given in tables 29, 30, and 31, as shown by the range values. Such variation underscores the fact that wastewater sludges are extremely heterogeneous materials. Therefore, it is extremely difficult, if not pointless, to try and compare characteristics between sludges unless the time is taken to consider all the conditions of sludge generation and treatment.

Table 29. Characteristics of New York-New Jersey sludges undergoing ocean disposal—1975 (ref. 61).

| Characteristic | Mean | Range | Number of Samples |
|---|---|---|---|
| Total solids (%) | 5.91 | 0.29-8.79 | 10 |
| Suspended solids (%) | 5.13 | 0.08-8.37 | 18 |
| Chemical oxygen demand (COD, g/kg) | 64.7 | 47.3-78.7 | 5 |
| Biochemical oxygen demand (BOD, g/kg) | 24.3 | 16.1-26.4 | 3 |
| Oil and grease (g/kg) | 9.1 | 0.9-14.6 | 21 |
| Chromium (mg/kg) | 23.3 | 0.8-120.0 | 25 |
| Total Cadmium (mg/kg) | 3.1 | 1.1-6.7 | 20 |
| Total Mercury (mg/kg) | 0.25 | 0.001-2.02 | 20 |
| Copper (mg/kg) | 64.0 | 2.8-75.0 | 26 |
| Lead (mg/kg) | 30.2 | 1.0-148.0 | 29 |
| Zinc (mg/kg) | 88.1 | 1.1-392.6 | 24 |
| Arsenic (mg/kg) | 4.0 | 0.004-40.0 | 24 |
| Nickel (mg/kg) | 6.85 | 0.02-16.62 | 26 |
| Vanadium (mg/kg) | 0.91 | 0.01-4.0 | 19 |
| Fecal coliform (organisms/100 ml × $10^5$) | 110 | 1.5-1600 | 17 |
| Specific gravity (g/g) | 1.059 | 1.005-1.276 | 11 |
| Petroleum hydrocarbons (mg/l) | 7,130 | 254-10,000 | 15 |

Table 30. Characteristics of New York-New Jersey sludges undergoing sludges disposal— 1976 (ref. 61).

| Characteristic | Mean | Range | Number of Samples |
|---|---|---|---|
| Total solids (%) | 4.76 | 1.21-9.66 | 43 |
| Suspended solids (%) | 4.32 | 0.99-8.87 | 40 |
| Chemical oxygen demand (COD, g/kg) | 44.6 | 12.2-134.8 | 21 |
| Biochemical oxygen demand (BOD, g/kg) | 22.5 | 4.5-45.8 | 11 |
| Oil and grease (g/kg) | 5.9 | 0.9-18.4 | 49 |
| Chromium (mg/kg) | 22.0 | 0.92-105.0 | 29 |
| Total Cadmium (mg/kg) | 2.03 | 0.05-11.06 | 39 |
| Total Mercury (mg/kg) | 0.32 | 0.012-3.35 | 42 |
| Copper (mg/kg) | 52.8 | 3.23-86.4 | 25 |
| Lead (mg/kg) | 31.82 | 0.12-223.0 | 30 |
| Zinc (mg/kg) | 102.6 | 0.6-230.5 | 25 |
| Arsenic (mg/kg) | 0.99 | 0.001-13.15 | 26 |
| Nickel (mg/kg) | 6.39 | 0.12-33.03 | 27 |
| Vanadium (mg/kg) | 0.52 | 0.02-1.50 | 20 |
| Fecal coliform (organisms/100 ml × $10^5$) | 47 | 0.11-1600 | 44 |
| Specific gravity (g/g) | 1.039 | 0.809-1.100 | 45 |
| Petroleum hydrocarbons (mg/l) | 9,108 | 350-79,400 | 36 |

Table 31. Characteristics of New York-New Jersey sludges undergoing ocean disposal— 1977 (ref. 61).

| Characteristic | Mean | Range | Number of Samples |
|---|---|---|---|
| Total solids (%) | 4.85 | 1.08-7.66 | 21 |
| Suspended solids (%) | 4.61 | 0.98-7.40 | 20 |
| Chemical oxygen demand (COD, g/kg) | 44.5 | 11.6-78.3 | 20 |
| Biochemical oxygen demand (BOD, g/kg) | 14.8 | 2.4-37.6 | 9 |
| Oil and grease (g/kg) | 9.3 | 0.4-30.6 | 22 |
| Chromium (mg/kg) | 33.3 | 1.0-192.9 | 21 |
| Total Cadmium (mg/kg) | 2.56 | 0.13-8.30 | 16 |
| Total Mercury (mg/kg) | 0.19 | 0.01-0.82 | 16 |
| Copper (mg/kg) | 57.8 | 17.2-133.5 | 21 |
| Lead (mg/kg) | 43.7 | 5.0-311.9 | 21 |
| Zinc (mg/kg) | 142.3 | 9.0-770.6 | 21 |
| Arsenic (mg/kg) | 0.27 | 0.009-2.50 | 21 |
| Nickel (mg/kg) | 12.25 | 0.03-62.37 | 21 |
| Vanadium (mg/kg) | 0.61 | 0.01-4.02 | 21 |
| Fecal coliform (organisms/100 ml × $10^5$) | 84 | 2-720 | 17 |
| Specific gravity (g/g) | 1.067 | 1.007-1.580 | 22 |
| Petroleum hydrocarbons (mg/1) | 2,602 | 361-6,665 | 14 |

While the data presented in tables 30, 31, and 32 was useful, further information was desired concerning the sludges being ocean disposed from New York and New Jersey. For example, what types of sludge were generated by the wastewater treatment systems, what were the sludge processing steps, was the anaerobic digestion process used, and, if so, what were its effects on sludge quality? Answers to such questions would provide more definitive information to compare to the Philadelphia situation.

Unfortunately, the EPA Region II ocean disposal permit records did not contain such information. Therefore, a questionnaire was developed to gather information on wastewater characteristics, industrial discharges, wastewater treatment processes, sludge/processing techniques, and the influence of the anaerobic digestion process. A copy of this questionnaire may be found in Appendix B. The questionnaire was mailed to all municipal wastewater treatment facilities listed in the EPA Region II ocean disposal permit records. After completed questionnaires were received, telephone calls were made to the treatment facilities to clarify questionnaire replies or gain additional information.

The information which was obtained by these methods is tabulated in table 32. Thirteen questionnaires were completed and returned. Unfortunately, no digested sludge data was submitted for the plants which utilized the anaerobic digestion process. In fact, essentially no raw sludge data was submitted. The majority of sludge characteristics data returned was a restatement of the ocean disposal permit monitoring values which have already been summarized in tables 29, 30, and 31.

The one surprising point which can be realized from inspection of table 32 is that the fraction of treatment systems using the anaerobic digestion process was smaller than anticipated. However, 10 of the 13 systems reporting were under 10 million gal (3785 $m^3$)/d in size. At smaller wastewater treatment plants, the anaerobic digestion process is not as commonly applied as anaerobic digestion or chemical stabilization.

One point which the questionnaire responses made very clear was that the types of sludge generated and the sludge treatment and disposal practices will be greatly changed in the future. Wastewater treatment system plant expansions and upgrading to meet strict Federal water quality standards will cause significant changes in the sludge characteristics reported in this chapter.

Table 32. Treatment system information from questionnaire responses.

| Treatment System | Average Flow (gal × $10^6$)/d | % Industrial Waste | Industry Types | Treatment Processes | Sludge Stabilization Processes |
|---|---|---|---|---|---|
| Linden Roselle Sewerage Authority, N.J. | 12 | 30 | Metal plating, slaughter house, coffee processing, pharmaceuticals | Primary sedimentation activated sludge | None |
| West Paterson, N.J. | 1.4 | 25 | Laundry, aluminum stripping plant | Primary sedimentation trickling filter | Anaerobic Digestion |
| Middlesex County Sewerage Authority, N.J. | 80-90 | 27 | Paper processing, yeast processing, plating, food processing, pharmaceuticals | Primary sedimentation activated sludge | Aerobic Digestion |
| Asbury Park, N.J. | 3.5 | 0 | ——— | Primary sedimentation | Anaerobic Digestion |
| Township of Morris, N.J., Woodland Plant | 1.25 | 8 | Research lab, chemical processing | Primary sedimentation activated sludge | Chlorine Oxidation |
| Township of Morris Butterworth Plant | 1.6 | 14 | Drug manufacturing, tea processing | Primary sedimentation activated sludge | Chlorine Oxidation |
| Passaic Valley Sewerage Commissioners, N.J. | 252 | 40.4 | Waste-paper reprocessing Textile processing | Primary sedimentation | None |
| Linpark, N.J. | 0.075 | 0 | ——— | Primary sedimentation extended aeration | None |
| West New York, N.J. | 8.5 | 10 | Dye processing, laundry | Primary sedimentation | None |
| Bergen County, N.J. | 0.75 | 0 |  | Primary sedimentation trickling filter | Aerobic Digestion |
| Northeast Monmouth County Regional Sewerage Authority, N.J. | 8 | < 1 | ——— | Activated sludge | Aerobic Digestion |
| Hudson County, N.J. | 5 | 100 | Chemical and food processing | Primary sedimentation | None |
| Township of Roxbury, N.J. | 1 | 0 | ——— | Primary sedimentation activated sludge | Aerobic Holding Tank |

# 6. CONCLUSIONS

Based on the information which has been discussed in the first five chapters of this study, the following conclusions may be reached with respect to the specific research questions originally stated:

(1) Specific differences do exist between the characteristics of primary and secondary wastewater sludges. The most significant differences rest with the nature of the solids particles and their size distribution. Based on these characteristic differences, it could be expected that remote sensing techniques would differentiate between true municipal primary and secondary sludges which have been disposed into the ocean. However, changes in the sludge solids particle characteristics which occur once the sludge is dispersed in seawater may mask or otherwise alter the observable differences. The subject of sludge-seawater interaction and modification of sludge particle characteristics clearly needs more definition.

(2) The wastewater sludges generated by the City of Philadelphia appear to possess characteristics similar to other east coast generated municipal wastewater sludges which are being ocean dumped. Given the complexities of determining sludge generation conditions and history, there is no reason to suspect that the Philadelphia sludges are unique.

(3). For the interpretation of remote sensing data monitored over City of Philadelphia ocean sludge disposal sites, the major influence on barged sludge characteristics is the anaerobic digestion process. In other words, the anaerobic digestion process exerts a more significant influence than the type of wastewater sludge (such as primary or secondary) generated. In the Philadelphia sludge disposal case, true primary and secondary sludges do not exist at the ocean disposal site. Instead, in the majority of instances, the barged sludge is a mixture of anaerobically digested primary and secondary sludges. Attempts to explain differences in observed remote sensing response to differences in sludge types, in the Philadelphia case, are in error. In any given sludge disposal situation, the anaerobic digestion process will tend to alter or homogenize the identifying characteristics of primary or secondary

# APPENDIX A

## ADDITIONAL SLUDGE CHARACTERISTICS

Table A-1. Concentrations of organic C, total N, P and S, $NH_4$ and $NO_3$ in sewage sludge (ref. 19).

| Element | Sample | | Range | Median | Mean |
|---|---|---|---|---|---|
| | Type[1] | Number | | | |
| Organic Carbon, % | Anaerobic | 31 | 18- 39 | 26.8 | 27.6 |
| | Aerobic | 10 | 27- 37 | 29.5 | 31.7 |
| | Other | 60 | 6.5- 48 | 32.5 | 32.6 |
| | All | 101 | 6.5- 48 | 30.4 | 31.0 |
| Total Nitrogen, % | Anaerobic | 85 | 0.5- 17.6 | 4.2 | 5.0 |
| | Aerobic | 38 | 0.5- 7.6 | 4.8 | 4.9 |
| | Other | 68 | <0.1- 10.0 | 1.8 | 1.9 |
| | All | 191 | <0.1- 17.6 | 3.3 | 3.9 |
| Ammonia Nitrogen, mg/l | Anaerobic | 67 | 120-67,600 | 1,600 | 9,400 |
| | Aerobic | 33 | 30-11,300 | 400 | 950 |
| | Other | 3 | 5-12,500 | 80 | 4,200 |
| | All | 103 | 5-67,600 | 920 | 6,540 |
| Nitrate Nitrogen, mg/l | Anaerobic | 35 | 2- 4,900 | 79 | 520 |
| | Aerobic | 8 | 7- 830 | 180 | 300 |
| | Other | 3 | - - --- | --- | 780 |
| | All | 45 | 2- 4,900 | 140 | 490 |
| Total Phosphorus, % | Anaerobic | 86 | 0.5- 14.3 | 3.0 | 3.3 |
| | Aerobic | 38 | 1.1- 5.5 | 2.7 | 2.9 |
| | Other | 65 | <0.1- 3.3 | 1.0 | 1.3 |
| | All | 189 | <0.1- 14.3 | 2.3 | 2.5 |
| Total Sulfur, % | Anaerobic | 19 | 0.8- 1.5 | 1.1 | 1.2 |
| | Aerobic | 9 | 0.6- 1.1 | 0.8 | 0.8 |
| | Other | -- | -- -- | -- | -- |
| | All | 28 | 0.6- 1.5 | 1.1 | 1.1 |

[1] "Other" includes lagooned, primary, tertiary and unspecified sludges. "All" signifies data for all types of sludges.

Table A-2. Concentrations of K, Na, Ca, Mg, Ba, Fe and Al in sewage sludge (ref. 19).

| Element | Sample Type[1] | Sample Number | Range | Median | Mean |
|---|---|---|---|---|---|
| Potassium, % | Anaerobic | 86 | 0.02- 2.64 | 0.30 | 0.52 |
| | Aerobic | 37 | 0.08- 1.10 | 0.38 | 0.46 |
| | Other | 69 | 0.02- 0.87 | 0.17 | 0.20 |
| | All | 192 | 0.02- 2.64 | 0.30 | 0.40 |
| Sodium, % | Anaerobic | 73 | 0.01- 2.19 | 0.73 | 0.70 |
| | Aerobic | 36 | 0.03- 3.07 | 0.77 | 1.11 |
| | Other | 67 | 0.01- 0.96 | 0.11 | 0.13 |
| | All | 176 | 0.01- 3.07 | 0.24 | 0.57 |
| Calcium, % | Anaerobic | 87 | 1.9- 20.0 | 4.9 | 5.8 |
| | Aerobic | 37 | 0.6- 13.5 | 3.0 | 3.3 |
| | Other | 69 | 0.1- 25.0 | 3.4 | 4.6 |
| | All | 193 | 0.1- 25.0 | 3.9 | 4.9 |
| Magnesium, % | Anaerobic | 87 | 0.03- 1.92 | 0.48 | 0.58 |
| | Aerobic | 37 | 0.03- 1.10 | 0.41 | 0.52 |
| | Other | 65 | 0.03- 1.97 | 0.43 | 0.50 |
| | All | 189 | 0.03- 1.97 | 0.45 | 0.54 |
| Barium, % | Anaerobic | 27 | <0.01- 0.90 | 0.05 | 0.08 |
| | Aerobic | 10 | <0.01- 0.03 | 0.02 | 0.02 |
| | Other | 23 | <0.01- 0.44 | <0.01 | 0.04 |
| | All | 60 | <0.01- 0.90 | 0.02 | 0.06 |
| Iron, % | Anaerobic | 96 | 0.1 - 15.3 | 1.2 | 1.6 |
| | Aerobic | 38 | 0.1 - 4.0 | 1.0 | 1.1 |
| | Other | 31 | <0.1 - 4.2 | 0.1 | 0.8 |
| | All | 165 | <0.1 - 15.3 | 1.1 | 1.3 |
| Aluminum, % | Anaerobic | 73 | 0.1 - 13.5 | 0.5 | 1.7 |
| | Aerobic | 37 | 0.1 - 2.3 | 0.4 | 0.7 |
| | Other | 23 | 0.1 - 2.6 | 0.1 | 0.3 |
| | All | 133 | 0.1 - 13.5 | 0.4 | 1.2 |

[1] "Other" includes lagooned, primary, tertiary and unspecified sludges. "All" signifies data for all types of sludges.

Table A-3. Concentrations of Mn, B, As, Co, Mo and Hg in sewage sludge (ref. 19).

| Element | Sample Type[1] | Sample Number | Range | Median | Mean |
|---|---|---|---|---|---|
| Manganese, mg/kg | Anaerobic | 81 | 58- 7,100 | 280 | 400 |
| | Aerobic | 38 | 55- 1,120 | 340 | 420 |
| | Other | 24 | 18- 1,840 | 118 | 250 |
| | All | 143 | 18- 7,100 | 260 | 380 |
| Boron, mg/kg | Anaerobic | 62 | 12- 760 | 36 | 97 |
| | Aerobic | 29 | 17- 74 | 33 | 40 |
| | Other | 18 | 4- 700 | 16 | 69 |
| | All | 109 | 4- 760 | 33 | 77 |
| Arsenic, mg/kg | Anaerobic | 3 | 10- 230 | 116 | 119 |
| | Aerobic | -- | -- -- | -- | -- |
| | Other | 7 | 6- 18 | 9 | 11 |
| | All | 10 | 6- 230 | 10 | 43 |
| Cobalt, mg/kg | Anaerobic | 4 | 3- 18 | 7.0 | 8.8 |
| | Aerobic | -- | -- -- | -- | -- |
| | Other | 9 | 1- 11 | 4.0 | 4.3 |
| | All | 13 | 1- 18 | 4.0 | 5.3 |
| Molybdenum, mg/kg | Anaerobic | 9 | 24- 30 | 30 | 29 |
| | Aerobic | 3 | 30- 30 | 30 | 30 |
| | Other | 17 | 5- 39 | 30 | 27 |
| | All | 29 | 5- 39 | 30 | 28 |
| Mercury, mg/kg | Anaerobic | 35 | 0.5-10,600 | 5 | 1,100 |
| | Aerobic | 20 | 1.0- 22 | 5 | 7 |
| | Other | 23 | 2.0- 5,300 | 3 | 810 |
| | All | 78 | 0.2-10,600 | 5 | 733 |

---

[1] "Other" includes lagooned, primary, tertiary and unspecified sludges. "All" signifies data for all types of sludges.

Table A-4. Concentrations of Pb, Zn, Cu, Ni, Cd and Cr in sewage sludge (ref. 19).

| Element | Sample | | Range | Median | Mean |
|---|---|---|---|---|---|
| | Type[1] | Number | | | |
| Lead, mg/kg | Anaerobic | 98 | 58-19,730 | 540 | 1,640 |
| | Aerobic | 57 | 13-15,000 | 300 | 720 |
| | Other | 34 | 72-12,400 | 620 | 1,630 |
| | All | 189 | 13-19,700 | 500 | 1,360 |
| Zinc, mg/kg | Anaerobic | 108 | 108-27,800 | 1,890 | 3,380 |
| | Aerobic | 58 | 108-14,900 | 1,800 | 2,170 |
| | Other | 42 | 101-15,100 | 1,100 | 2,140 |
| | All | 208 | 101-27,800 | 1,740 | 2,790 |
| Copper, mg/kg | Anaerobic | 108 | 85-10,100 | 1,000 | 1,420 |
| | Aerobic | 58 | 85- 2,900 | 970 | 940 |
| | Other | 39 | 84-10,400 | 390 | 1,020 |
| | All | 205 | 84-10,400 | 850 | 1,210 |
| Nickel, mg/kg | Anaerobic | 85 | 2- 3,520 | 85 | 400 |
| | Aerobic | 46 | 2- 1,700 | 31 | 150 |
| | Other | 34 | 15- 2,800 | 118 | 360 |
| | All | 165 | 2- 3,520 | 82 | 320 |
| Cadmium, mg/kg | Anaerobic | 98 | 3- 3,410 | 16 | 106 |
| | Aerobic | 57 | 5- 2,170 | 16 | 135 |
| | Other | 34 | 4- 520 | 14 | 70 |
| | All | 189 | 3- 3,410 | 16 | 110 |
| Chromium, mg/kg | Anaerobic | 94 | 24-28,850 | 1,350 | 2,070 |
| | Aerobic | 53 | 10-13,600 | 260 | 1,270 |
| | Other | 33 | 22-99,000 | 640 | 6,390 |
| | All | 180 | 10-99,000 | 890 | 2,620 |

[1] "Other" includes lagooned, primary, tertiary and unspecified sludges. "All" signifies data for all types of sludges.

# APPENDIX B

## QUESTIONNAIRE

### Characteristics and Processing
### Ocean Disposal Sewage Sludge

Please answer all the questions applicable to your wastewater treatment plant. If not applicable, mark N/A in front of that question(s).

Many treatment systems are undergoing expansion or process revision, complicating the description of treatment facilities or sludge characteristics. Most of the NASA remote sensing experiments were conducted in 1976-77. Therefore, the following questions pertain to the status of your system during that time period. However, your description of current and/or future process configurations will be very helpful, if such information is available.

1) What is the average wastewater flow rate to your treatment plant?

_______________ MGD

2) What is the estimated percentage of your total flow contributed by industrial sources?

____________ %

Are there any particular types of industry which influence wastewater or sludge characteristics (e.g., metal plating operations, refineries, etc.)?

_______________________________________________

_______________________________________________

_______________________________________________

3) What are the types of wastewater treatment processes in use? (Check those applicable)

_____ Primary Sedimentation
_____ Activated Sludge
_____ Trickling Filters
_____ Rotating Biological Contactors
_____ Disinfection
_____ Chemical Precipitation
_____ Filtration
_____ Activated Carbon Adsorption
_____ Others, please explain

Please supply a simple diagram showing treatment steps or verbally describe your system.

Additional space for treatment system diagram.

4) Are sludge types combined or kept separate during sludge processing steps? (For example, are primary and secondary sludges combined prior to anaerobic digestion, dewatering, lagooning, and/or ocean disposal?)

5) What types of sludge treatment processes are in use? (Check those applicable and indicate sludge type)

| | | Sludge Type |
|---|---|---|
| ______ | Gravity Thickening | ______________________ |
| ______ | Flotation Thickening | ______________________ |
| ______ | Aerobic Digestion | ______________________ |
| ______ | Anaerobic Digestion | ______________________ |
| ______ | Lagooning | ______________________ |
| ______ | Chemical Conditioning | ______________________ |
| ______ | Heat Treatment | ______________________ |
| ______ | Drying Beds | ______________________ |
| ______ | Vacuum Filtration | ______________________ |
| ______ | Centrifugation | ______________________ |
| ______ | Pressure Filtration | ______________________ |
| ______ | Wet Oxidation | ______________________ |
| ______ | Elutriation | ______________________ |
| ______ | Others, please explain | ______________________ |

Please supply a simple diagram showing sludge processing steps or verbally describe your system.

6) If anaerobic digestion is utilized, what are the average raw sludge and digested sludge characteristics? Record whatever characteristics are available on the following table and indicate units (mg/l, mg/kg, etc.)

| Characteristic | Raw Sludge | | Digested Sludge | |
|---|---|---|---|---|
| | Average | Range | Average | Range |
| Total Solids | | | | |
| Suspended Solids | | | | |
| Volatile Solids | | | | |
| Volatile Suspended Solids | | | | |
| Specific Gravity | | | | |
| pH | | | | |
| BOD | | | | |
| COD | | | | |
| TOC | | | | |
| Oil and Grease | | | | |
| Hydrocarbons | | | | |
| Total Alkalinity | | | | |
| TKN | | | | |
| $NH_3$-N | | | | |
| $NO_3$-N | | | | |
| Total Coliform | | | | |
| Fecal Coliform | | | | |
| Total Phosphorus | | | | |
| Chromium | | | | |
| Cadmium Liquid | | | | |
| Cadmium Solid | | | | |
| Copper | | | | |
| Lead | | | | |
| Zinc | | | | |
| Arsenic | | | | |
| Nickel | | | | |
| Vanadium | | | | |
| Mercury Liquid | | | | |
| Mercury Solid | | | | |
| Particle Size Distribution | | | | |

7) Are the processed sludges lagooned prior to ocean disposal?

Yes No

If yes, what is the approximate storage time? ____________________

8) a) Name of wastewater treatment plant ____________________

____________________

b) Your name ______________________________
c) Title ______________________________
d) Date ____________________
e) Telephone number with area code ______________

9) Additional facts or statements which you feel may be helpful or required for clarity.

THANK YOU FOR YOUR HELP!

# REFERENCES

1. Burd, R.S.: A Study of Sludge Handling and Disposal. U.S. Dept. of Interior, Fed. Water Poll. Control Admin., Washington, DC, May 1968.

2. Dick, R.I.: Attitudes in Sludge Treatment and Disposal. J. Environ. Eng. Div., Amer. Soc. Civil Engrs., Vol EE5, No. 1077, 1974.

3. Multimedium Management of Municipal Sludge. National Academy of Sciences, Washington, DC, 1978.

4. Guarino, C.F.; Nelson, M.D.; and Townsend, S.: Philadelphia Sludge Disposal in Coastal Waters. J. Water Poll. Control Fed., Vol. 49, p. 737, 1977.

5. Hadeed, S.J.: Ocean Dumping Phase-Out in EPA Region II. J. Water Poll. Control Fed., Vol. 48, p. 2246, 1976.

6. Kendrick, P.J.: Remote Sensing and Water Quality. J. Water Poll. Control Fed., Vol. 48, p. 2243, 1976.

7. Usry, J.W.; Witte, W.G.; Whitlock, C.H.; and Gurganus, E.A.: Laboratory Upwelled Spectral Signature Measurements of Sewage Sludge for Remote Sensing of Ocean Dumping. Presented by NASA/LaRC at 1977 IEEE Southeastern, Williamsburg, VA, Apr. 4-6, 1977.

8. Johnson, R.W.: Multispectral Analysis of Ocean Dumped Materials. Presented by NASA/LaRC at the 11th International Symposium on Remote Sensing of the Environment, Ann Arbor, MI, Apr. 25-29, 1977.

9. Johnson, R.W.: Identification and Mapping of Pollution Features in the Coastal Zones. Presented by NASA/LaRC at IEEE Southeastern, Williamsburg, VA, Apr. 4-6, 1977.

10. Johnson, R.W.; Ohlhorst, C.W.; and Usry, J.W.: Location, Identification, and Mapping of Sewage Sludge and Acid Waste Plumes in the Atlantic Coastal Zones. Presented by NASA/LaRC at the 4th Joint Conference on Sensing of Environmental Pollutants, New Orleans, LA, Nov. 6-11, 1977.

11. New York State Department of Health: Manual of Instruction for Sewage Treatment Plant Operators. Health Education Service, Albany, NY, 1965.

12. Fair, G.M.; Geyer, J.C.; and Okun, D.A.: Water and Wastewater Engineering Vol. 2, John Wiley & Sons, Inc., NY, 1968.

13. Metcalf and Eddy, Inc.: Wastewater Engineering: Treatment, Disposal, Reuse, 2nd ed., McGraw-Hill, Inc., NY, 1979.

14. McKinney, R.E.: Microbiology for Sanitary Engineers. McGraw-Hill, Inc., NY, 1962.

15. Process Control Manual for Aerobic Biological Wastewater Treatment Facilities. EPA-430/9-77-006, Washington, DC, Mar. 1977.

(cont'd)

16. Waller, R.: Impact of Sewage Treatment and Operations on Sludge Handling and Disposal. In: Sludge Management Disposal and Utilization. Information Transfer Inc., Rockville, MD, 1977.

17. Hecht, N.L.; Duvall, D.S.; and Rashidi, A.S.: Characterization and Utilization of Municipal and Utility Sludges and Ashes. Vol. II. Municipal Sludges. EPA-670/2-75-033b, May 1975.

18. Farrell, J.B.: Overviews of Sludge Handling and Disposal. Municipal Sludge Management. Information Transfer Inc., Rockville, MD, 1974.

19. Municipal Sludge Management: Environmental Factors. Tech. Bull. EPA-430/9-77-004, Oct. 1977.

20. Dean, R.B., and Smith, J.E., Jr.: The Properties of Sludges. In: Recycling Municipal Sludges and Effluents on Land. Nat'l. Assoc. of State Universities and Land-Grant Colleges, Washington, DC, 1973.

21. Carnes, B.A.; and Eller, J.M.: Characterization of Wastewater Solids. J. Water Poll. Control Fed., Vol. 44, p. 1498, 1972.

22. Sawyer, C.N.; and McCarty, P.L.: Chemistry for Environmental Engineering. 3rd. ed., McGraw-Hill, Inc., NY, 1978.

23. Standard Methods for the Examination of Water and Wastewater. 14th ed., Amer. Pub. Health Assoc., Amer. Water Works Assoc., and Water Poll. Control Fed., 1976.

24. Vesilind, P.A.: Treatment and Disposal of Wastewater Sludges. Ann Arbor Science Publishers, Inc., MI, 1974.

25. Browne, D.W.; and Callaway, R.J.: Dispersion of Sewage Sludge Discharged from Sludge Disposal Vessels into New York Bight. Data Report I, Vol. III, Laboratory Studies of Physical and Settling Characteristics of Sewage Sludge. EPA, Corvallis, OR.

26. Process Design Manual for Sludge Treatment and Disposal. EPA 625/1-74-006, Oct. 1974.

27. Stern, G.; and Farrell, J.B.: Sludge Disinfection Techniques. In: Composting of Municipal Residues and Sludges. Information Transfer, Inc., Rockville, MD, 1978.

28. Assessing Potential Ocean Pollutants. Nat'l Academy of Science, Washington, DC, 1975.

29. Rudolfs, W.; and Balmat, J.L.: Colloids in Sewage. I. Separation of Sewage Colloids with the Aid of the Electron Microscope. Sew. and Ind. Wastes, Vol. 24, p. 247, 1952.

(cont'd)

## REFERENCES (CONT'D)

30. Karr, P.R., III: Factors Influencing the Dewatering Characteristics of Sludge. Ph.D. Dissertation, Clemson Univ., 1976.

31. Robeck, G.G.: High Rate Filtration Study at Gaffney, S.C. Water Plant. U.S. Public Health Service, Taft Sanitary Eng. Center, Cincinnati, OH, 1963.

32. Finstein, M.S.; and Heukelekian, H.: Gross Dimensions of Activated Sludge Flocs with Reference to Bulking. J. Water Poll. Control Fed., Vol. 39, No. 33, 1967.

33. Johnson, R.W.; Duedall, I.W.; Glasgow, R.M; Proni, J.R.; and Nelsen, T.A.: Quantitative Mapping of Suspended Solids in Wastewater Sludge Plumes in the New York Bight Anex. J. Water Poll. Control Fed., Vol. 49, p 2063, 1977.

34. Powell, J.B.; Miller, A.C.; and Winstead, E.L.: Ground Truth Analysis for an Ocean Dump, April 13, 1978. Unpub. Tech. Rep., NASA/Langley Res. Center, Hampton, Va., June 7, 1978.

35. Ham, R.K.; and Christman, R.F.: Agglomerate Size Changes in Coagulation. J. San. Eng. Div., Amer. Soc. Civil Engrs., Vol. SA3, p. 481, 1969.

36. Bargmann, R.D.; Garber, W.F.; and J. Nagano: Sludge Filtration and Use of Synthic Organic Coagulants at Hyperion. Sew. and Ind. Wastes, Vol. 30, p. 1079, 1958.

37. Karr, P.R.; and Keinath, T.M.: Influence of Particle Size on Sludge Dewaterability. J. Water Poll. Control Fed., Vol. 50, p. 1911, 1978.

38. Eckenfelder, W.W.; and Ford, D.L.: Water Pollution Control—Experimental Procedures for Process Design. Jenkins Publishing Co., NY, 1970.

39. Mead, R.H.: Transport and Deposition of Sediments in Estuaries. In: Environmental Framework of Coastal Plan Estuaries. The Geological Soc. of Amer., Memoir 13, 1972.

40. Wankoff, William, Chief, Wastewater Treatment Section, Water Dept., Philadelphia, PA. (Personal Communication), Oct. 1977.

41. Anaerobic Sludge Digestion. Manual of Practice No. 16, Water Poll. Control Fed., Washington, DC, 1968.

42. Utilization of Municipal Wastewater Sludge. Manual of Practice No. 2, Water Poll. Control Fed., Washington, DC, 1971.

43. Operations Manual—Anaerobic Sludge Digestion. EPA 430/9-76-001, Washington, DC, Feb. 1976.

44. Clark, J.W.; Viessman, W., Jr.; and Hammer, M.J.: Water Supply and Pollution Control. 3rd ed., Harper and Row, Inc., NY, 1977.

(cont'd)

45. Coackley, P.; and Allos, R.: The Drying Characteristics of Some Sewage Sludge. Inst. of Sew. Purif. J. Proc., Vol. 6, p. 557, 1962.

46. Garber, W.F.: Plant Scale Studies of Thermophilic Digestion at Los Angeles. Sew. and Ind. Wastes, Vol. 26, p. 1202, 1956.

47. Garber, W.F.; Ohara, G.T.; Colbaugh, J.E.; and Raksit, S.K.: Thermophilic Digestion at the Hyperion Treatment Plant. J. Water Poll. Control Fed., Vol. 47, p. 950, 1975.

48. Hansen, B.E.; Smith, D.L.; and Garrison, W.E.: Startup Problems of Sludge Dewatering Facility. Presented at the 51st Annual Water Poll. Control Fed. Conf., Anaheim, CA, Oct. 3, 1978.

49. Notice of Public Hearing—Application for an Interim Permit to Transport and Dump Materials into Ocean Waters — City of Philadelphia. EPA, Region III, April 11, 1978.

50. Northeast Water Pollution Control Plant. System Information Booklet prepared for the 50th Annual Conference of the Water Poll. Control Fed. City of Philadelphia, PA Water Dept., Oct. 1977.

51. Northeast Water Pollution Control Plant Fiscal 1977 Annual Report. City of Philadelphia, PA Water Dept., 1977.

52. Southwest Water Pollution Control Plant. System Information Booklet prepared for the 50th Annual Conference of the Water Poll. Control Fed. City of Philadelphia, PA Water Dept., Oct. 1977.

53. Southeast Water Pollution Control Plant Fiscal 1977 Annual Report. City of Philadelphia, PA Water Dept., 1977.

54. Southeast Water Pollution Control Plant. System Information Booklet prepared for the 50th Annual Conference of the Water Poll. Control Fed. City of Philadelphia, PA Water Dept., Oct. 1977.

55. Water for Tomorrow. A Biennial Report of the Philadelphia Water Department, 1973-1975. City of Philadelphia, PA Water Dept., 1976.

56. Guarino, C.F.; and Townsend, S.: Ocean-Disposal Experiences in Philadelphia. In: Municipal Sludge Measurement. Information Transfer, Inc. Rockville, MD, 1974.

57. Final Revision of the Ocean Dumping Regulations and Criteria. EPA article in Federal Register, Vol. 42, No. 7, Jan. 11, 1977.

58. Notice of Public Hearing — Application for an Interior Permit to Transport and Dump Materials into Ocean Waters — City of Philadelphia. EPA Region III, Philadelphia, PA, Mar. 26, 1976.

(cont'd)

# REFERENCES (CONCL'D)

59. City of Philadelphia—Barged Sludge Data Sheets. Obtained from William Wankoff, P.E., Chief, Wastewater Treatment Station, Water Dept., Philadelphia, PA, Aug. 1978.

60. Nelson, M.D.; Townsend, S.A.; Lauletta, T.; and Senske, F.: Philorganic. In: Sludge Management Disposal and Utilization. Information Transfer Inc., Rockville, MD, 1977.

61. United States Environmental Protection Agency Ocean Disposal Permit Records. Region II, Edicon, NJ, June 1978.