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SLUDGE DIGESTION PRACTICES ON OAHU, HAWAII

by

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ABSTRACT

Characteristics and treatment efficiency of the sludge digestion facilities at four sewage treatment plants of the City and County of Honolulu, one each at Kaneohe, Kailua (both secondary treatment-trickling filter plants), and Pearl City (primary treatment), which utilize anaerobic digestion systems and the fourth at Mililani (secondary treatment-activated sludge), which utilizes an aerobic digestion system were studied over a two-week period at each plant. Included in the study were both raw and digested sludges.

Overall results indicate that the digestion systems were operating generally within accepted ranges for parameters tested. The Kaneohe plant had a volatile solids reduction of 64 percent, solids retention time of 143 days, and methane:carbon dioxide gas yield percentage of 67:33. The Kailua plant had a volatile solids reduction of 30 percent, solids retention time of 32 days, and methane:carbon dioxide gas yield percentage of 66:34. The Pearl City plant had a volatile solids reduction of 64 percent, solids retention time of 10 days and methane:carbon dioxide gas yield percentage of 64:36. The Mililani plant had a volatile solids reduction of 49 percent with a sludge age of 36 days.

It was concluded that the three anaerobic digestion systems were operating satisfactorily although not at optimum efficiency. The Mililani plant achieved a reasonable digestion efficiency although operational problems were indicated because of low pH and ORP values for the sludge and high specific resistance values for the digested sludge.

It was recommended that a program of regular monitoring of sludge characteristics and digestion treatment efficiency be initiated to assist in plant operations at all sites.

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INTRODUCTION

Environmental pollution has reached a very critical situation today because of several factors. Hollis (1961) stated:

> The growing population and developing industry will produce metropolitan and industrial wastes high in volume. Increased use of pesticides, insecticides and detergents is an example of this problem. These synthetic organics do not break down like natural organics and many of these are difficult to treat or remove from wastewaters. Most of these wastes were practically non-existent in 1940. Now they are present in concentrations up to 0.5 mg/l in several major streams. These untreated organic and industrial wastes which are daily discharged into streams, rivers, and lakes have increased far beyond the capacity of those receiving waters to absorb them.

In the case of a rapidly growing population living on a water course of a limited volume, it is obvious that the fresh water has to be protected and wastewater treated before it is discharged into such natural receiving waters.

Generally, wastewater treatment processes separate the liquid and solid portions of the wastewater. The liquid, or the effluent from the wastewater treatment plant, is disposed of by dilution into receiving waters or on land. The solids, which form sludge, are disposed of by various physical and chemical means, such as by direct spreading on land or by reduction in volume through digestion.

The major function of digestion is to stabilize raw sludge, reduce its volume, and make it more acceptable for final disposal. The most common methods of processing organic sludges are anaerobic digestion and aerobic oxidation. Schlenz (1951) reported that digestion is economical and desirable, even as an addition to the filtration and incineration processes because (i) the required capacity of the filtration and incineration equipment is reduced by about three-fourths or by 40 to 50 percent, (ii) chemical feed for sludge conditioning is substantially reduced, (iii) sludge handling equipment is reduced in size and power requirement because of the lower moisture content and reduced volume of the digested sludge, and (iv) the occurrence of odors is reduced.

Sludge digestion is influenced by many factors. These factors are loading, detention time, pH (hydrogen ion concentration), ORP (oxidation-reduction potential), total solids, volatile solids, volatile acids, alkalinity, COD (chemical oxygen demand), gas production (of carbon dioxide and methane), and the concentrations of alkali and alkaline-earth cations in the sludge as well as the mass and type of bacterial flora present. Good digestion will depend on the balance of all related factors and not on any single one.

Purpose of the Study

A better understanding of the digestion practices of wastewater treatment plants will improve operation of those facilities and result in more efficient and economical plant operation treatment. Hence, this study was conducted to determine the characteristics of both raw sludge and digested sludge produced at different types of wastewater treatment plants utilized on Oahu and to obtain information about the condition of the principal solids handling units of the plants as well as the loading rates of the various processing units.

Study Sites

The plants selected for study were those operated by the City and County of Honolulu for the treatment of principally domestic sewages and are located at Kailua, Kaneohe, Pearl City, and Mililani Town. Treatment plant locations are shown in Figure 1.

The Kailua and Kaneohe treatment plants provide secondary treatment with biofiltration and anaerobic digestion systems. The Pearl City plant provides only primary treatment with anaerobic digestion. The Mililani plant utilizes a "Rapid-Bloc" (Chicago Pump Co.) activated sludge process with aerobic digestion. Plant flow diagrams of the treatment plants are shown in Figures 2 to 5.

SAMPLING AND ANALYTIC PROCEDURES

Each plant was checked six times on Monday, Wednesday, and Friday for two weeks. Four raw sludge samples were collected every two hours starting at 7 a.m. On each sampling day, one digested sludge sample and one gas sample was obtained (except at Mililani, since it had an aerobic

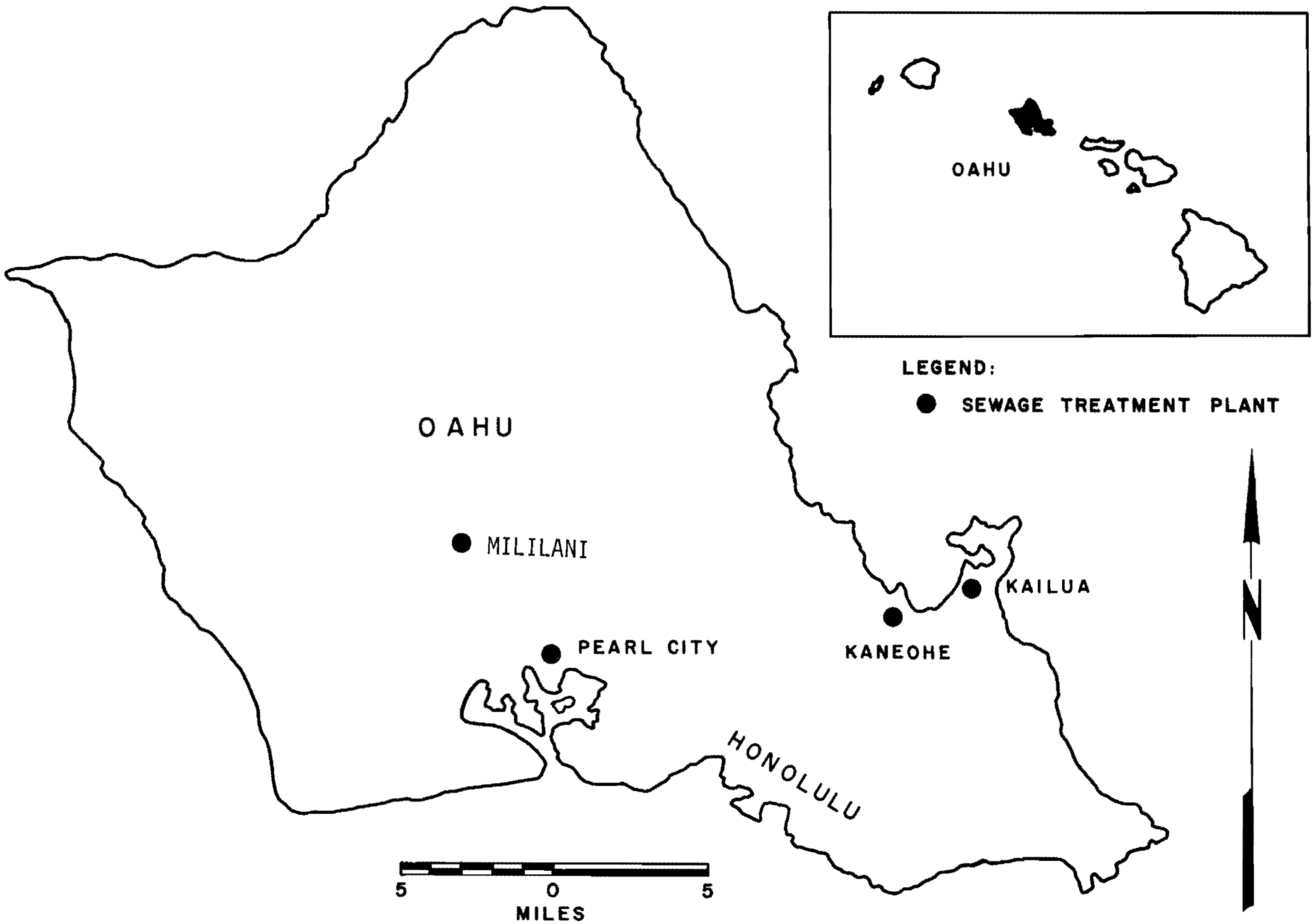

FIGURE 1. LOCATION MAP OF THE FOUR SEWAGE TREATMENT PLANTS.

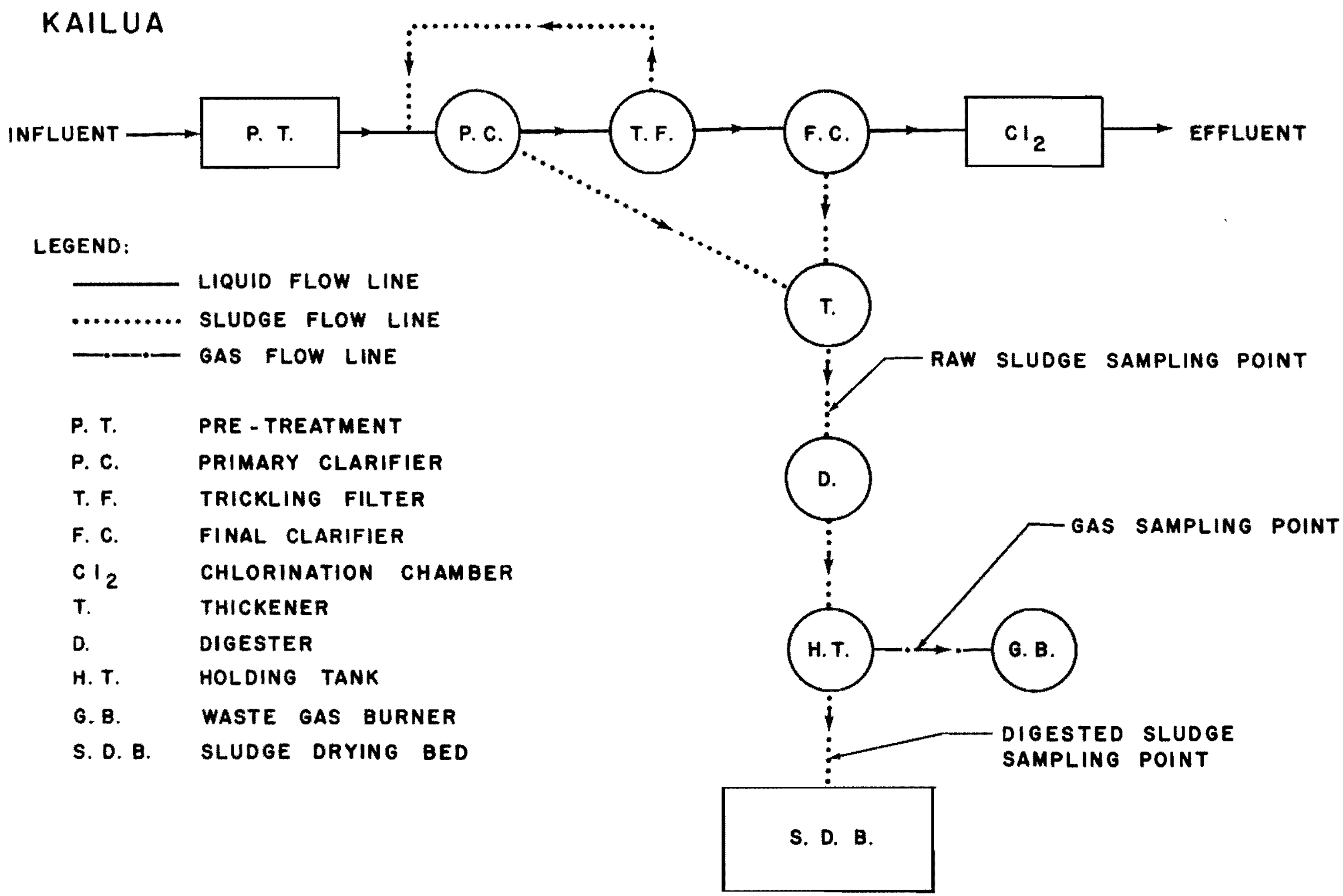

FIGURE 2. FLOW DIAGRAM AND SAMPLING POINTS AT KAILUA SEWAGE TREATMENT PLANT.

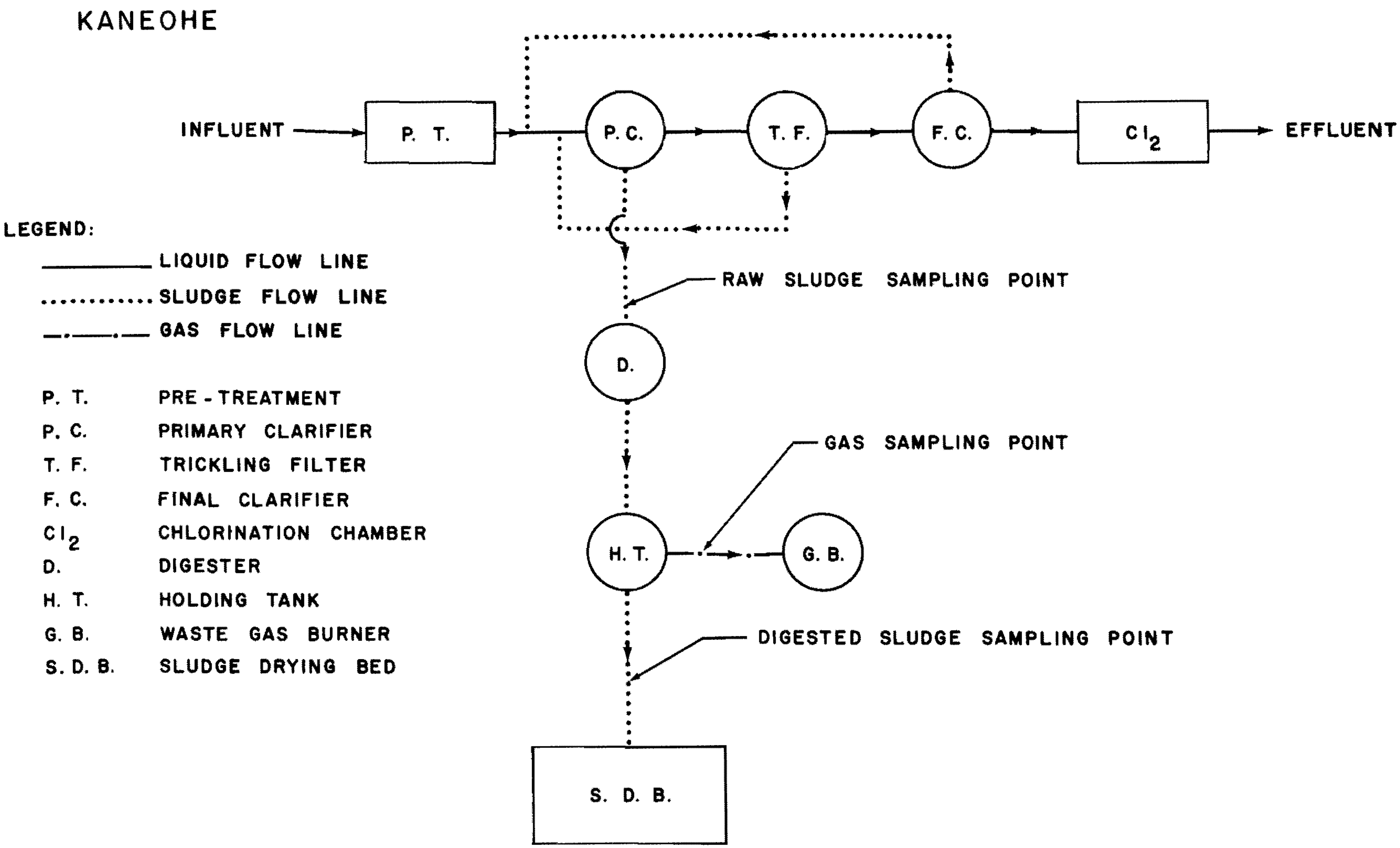

FIGURE 3. FLOW DIAGRAM AND SAMPLING POINTS AT KANEOHE SEWAGE TREATMENT PLANT.

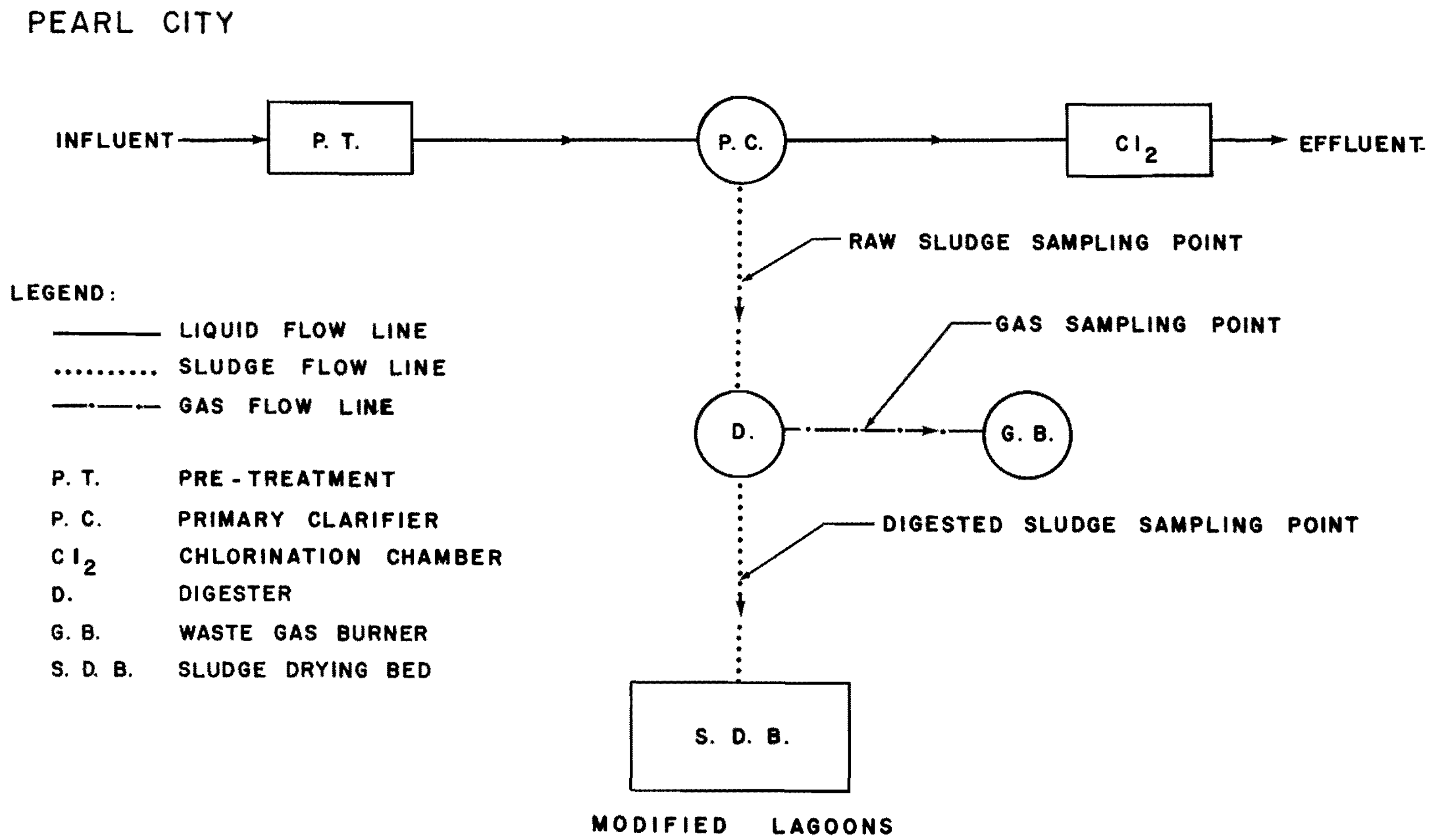

FIGURE 4. FLOW DIAGRAM AND SAMPLING POINTS AT PEARL CITY SEWAGE TREATMENT PLANT.

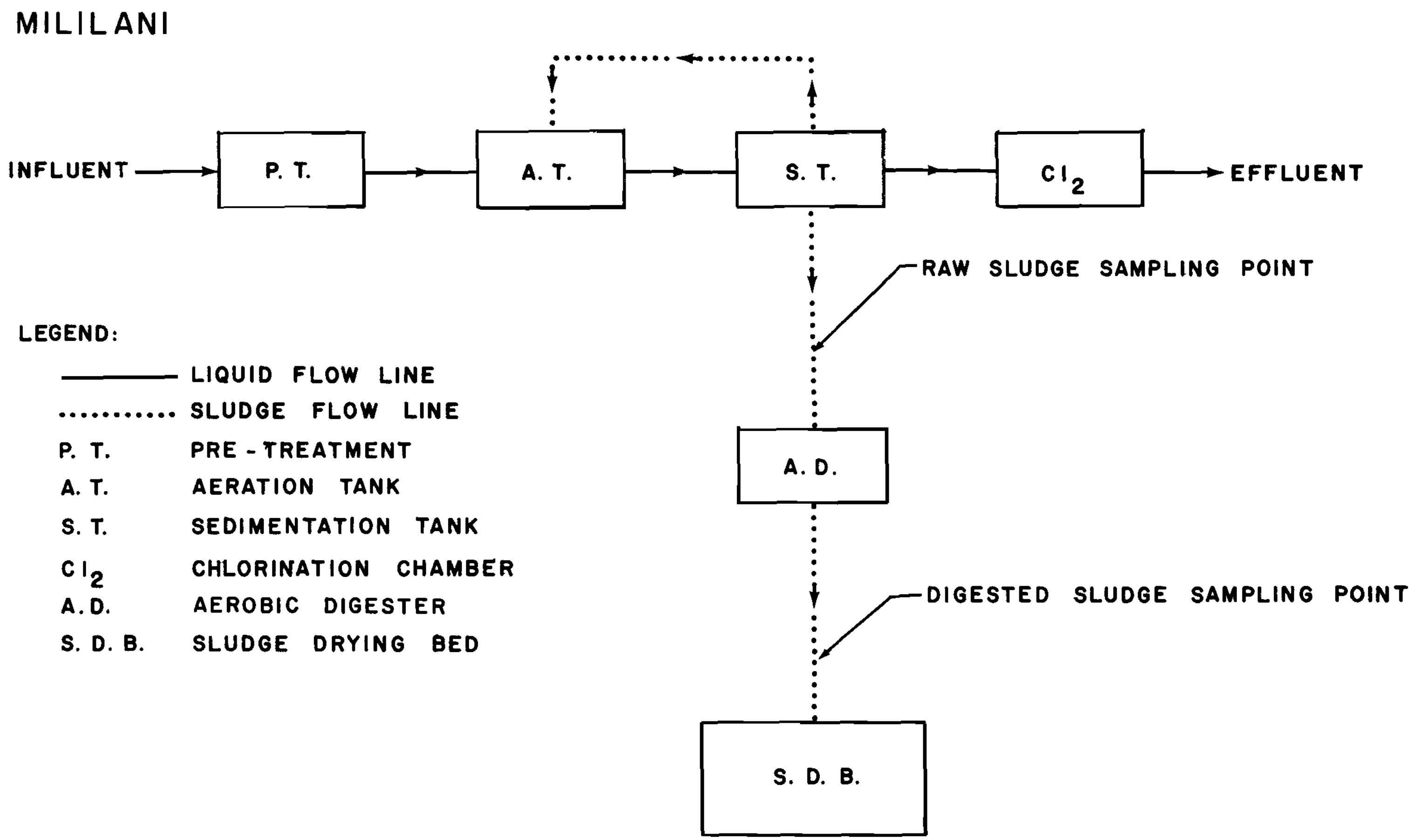

FIGURE 5. FLOW DIAGRAM AND SAMPLING POINTS AT MILILANI SEWAGE TREATMENT PLANT.

digester no gas was obtained there). Measurement of pH and ORP was done in the field by City and County personnel. The samples were then held under refrigeration and transported to the Environmental and Sanitary Engineering Laboratory of the University of Hawaii for further analyses.

Both raw sludge samples and digested samples were collected in 1.5 gallon plastic bottles from the respective pumping lines. Gas samples were collected in one-foot diameter plastic balloons from waste-gas lines leading to the waste-gas burners.

ORP (oxidation-reduction potential) and pH analyses were made by plant analysts in the field. The pH and ORP data together with sludge pumping and draw-off rates were furnished by the City and County Sewer Division.

The analyses of total solids, total volatile solids, COD, alkalinity, specific resistance to dewatering, CO_2-CH_4 content, chloride, sodium, and calcium were done at the Environmental and Sanitary Engineering Laboratory.

Procedures given in *Standard Methods* (American Public Health Association, 1965) for testing total solids, total volatile solids, COD, and alkalinity were followed.

The Buchner funnel vacuum filtration test was used for determining the specific resistance to dewatering (Water Pollution Control Federation, 1968).

An Orsat Analyzer (Model 621A-32.30, the Hays Corporation, Michigan City) was used for CO_2, CO, and O_2 analyses. Methane was obtained by difference, assuming that the gas sample was composed only of CO_2 and CH_4. The oxygen in the samples was measured to determine the residual air volume in the collection balloon. The CO_2-CH_4 readings were corrected once this volume was computed.

The concentration of chloride ion in the sludge was determined by specific ion electrode. Validity of the electrode results was checked by titration using the mercuric nitrate method in *Standard Methods* (American Public Health Association, 1965). In comparing the results of the two methods, the concentrations obtained by ion electrode were about ten percent higher than those obtained by the mercuric nitrate method in the range of 500 to 2,800 mg/l. However, below a concentration of 300 mg/l the results by titration were about 13 percent higher.

Sodium ion and calcium ion were measured by flame photometry.

PLANT OPERATION PROCEDURES AND RESULTS

The type of treatment, design flow, sludge pumping rate,. pumping frequency, and sludge quantity drawn into the digestors each day at the four sewage treatment plants studied are listed in Table 1.

TABLE 1. PLANT OPERATIONAL DATA.

PLANT	TYPE OF TREATMENT	DESIGN FLOW MGD	SLUDGE PUMPING RATE GAL/MIN	FREQUENCY	SLUDGE QUANTITY	
					RAW SLUDGE GAL/DAY	DIGESTER SLUDGE GAL/WEEK
KAILUA	SECONDARY-TRICKLING FILTER AND THICKENER	7.00	130	4 MIN/ HR	12480	20000
KANEOHE	SECONDARY-TRICKLING FILTER	4.30	70	15 MIN/ 2 HR	12000	16000
PEARL CITY	PRIMARY	5.00	270	6 MIN/45 MIN	25000	25000$^{\Delta}$
MILILANI	SECONDARY-ACTIVATED SLUDGE PROCESS	0.93	80	8 MIN/ 6 HR	2560	16000*

$^{\Delta}$GAL/DAY

*GAL/12 DAYS

Comparison of some digester operational data is listed in Table 2, including the type of digestion process, solids loadings, detention time digestion temperature, and solids attention time. It can be seen that the loading rates for Kailua and Kaneohe are in an acceptable range. The loading rates at Pearl City and Mililani appear to be lower than is the accepted practice. The detention times and digestion temperatures are also within the ranges reported in the literature. However, a raise in digestion temperature at the Pearl City plant to about 95°F may result in an increased volatile solids reduction.

A very important parameter governing the efficiency and operation of anaerobic digestion is the biological solids retention time. This is similar to the sludge-age concept used in activated sludge treatment and is defined as the ratio of the total weight of suspended solids in treatment to the total weight of suspended solids leaving the system per day. The solids retention time relates treatment operation to the age and quantity of microorganisms in the system and is a sound parameter for design. A major requirement of both the conventional and the high-rate anaerobic digestion process is that the solids retention time be at least ten days for a temperature of operation of 95°F. The required solids retention time is approximately doubled for each 20°F decrease in temperature from the normal range (McCarthy, 1964).

TABLE 2. DIGESTER OPERATIONAL DATA.

PLANT	DIGESTION PROCESS	LB VS/CF/DAY	LB VS/CAP/DAY	DETENTION TIME DAYS	DIGESTION TEMPERATURE °F	SOLIDS RETENTION TIME DAYS
KAILUA	CONVENTIONAL ANAEROBIC	0.071	0.061	48	96-99	32
KANEOHE	CONVENTIONAL ANAEROBIC	0.050	0.086	52	90-100	143
PEARL CITY	HIGH-RATE ANAEROBIC	0.055	0.115	22	86-88	10
MILILANI[a]	AEROBIC	0.029	0.022	12	70-85	36[b]
REPORTED PRACTICE	CONVENTIONAL ANAEROBIC	0.03 -0.135[c]		11-90[d]	85-120	MIN 10 DAYS
REPORTED PRACTICE	HIGH-RATE ANAEROBIC	0.1 -0.575[e]		2.6-31[f]	85-120	MIN 10 DAYS
REPORTED PRACTICE	AEROBIC	0.048-0.145[g]		10-20[h]		

a. SLUDGE OXIDATION RATE = 21 mg/1 O_2/HOUR
b. SLUDGE AGE
c. REFERENCES
d. BURD (1968), ECKENFELDER AND O'CONNOR (1966).
e. WPCF (1968), BURD (1968), TORPEY (1954).
f. BURD (1968), ECKENFELDER AND O'CONNOR (1966), TORPEY (1954), BLODGETT (1956), SAWYER AND GRUMBLING (1960).
g. DREIER (1963).
h. DREIER (1963), BARNHART (1961), VIRARAGHAVAN (1965).

The solids retention times for the three anaerobic digestion plants are considered to be satisfactory. The Pearl City plant is operated at less than optimum temperature range. An increase in temperature to 95°F should yield a longer solids retention time and increased volatile solids reduction.

Sludge age in aerobic digestion is similar to solids retention time in anaerobic digestion. Sludge age is defined as the ratio of the weight of volatile solids in the digester to the weight of volatile solids added daily. The sludge age of 36 days for the Mililani plant is considered adequate.

The same plant had a sludge oxidation rate of 21 ppm O_2/hr with an average temperature of 25°C, a rate that is considered low compared to reported data in the literature. Loehr (1965) reported that sludge oxidation rates vary, depending on the sludge microbial population, the characteristics of the raw waste, the sludge age, and the sludge temperature.

The general sludge conditions observed for the four plants are listed in Table 3. Both the Kailua and Kaneohe plants had low pH values for raw and digested sludge. One reason for this may be that these two plants receive septic sewage from cesspools in their surrounding area. A raise in pH of the raw sludge by the addition of lime may result in better digestion. The pH values for Pearl City are satisfactory. The pH value of 6.38 of raw sludge for the Mililani plant is close to the optimum range but that of the digested sludge is quite low.

TABLE 3. GENERAL SLUDGE CONDITIONS.

PLANT	SAMPLE	pH	ORP mv	VOLATILE ACIDS mg/l	ALKALINITY mg/l	GAS COMPONENT CO_2	GAS COMPONENT CH_4
KAILUA	RAW	5.8	-287	543	853		
	DIGESTED	6.2	-283	157	2258	34	66
KANEOHE	RAW	4.7	-127	1017	459		
	DIGESTED	6.6	-166	253	2632	33	67
PEARL CITY	RAW	6.0	-197	606	334		
	DIGESTED	7.0	-204	124	1513	36	64
MILILANI	RAW	6.4	-109	97	156		
	DIGESTED	5.1	+ 44	256	99		
REPORTED PRACTICE							
CONVENTIONAL ANAEROBIC	RAW			500-2500[a]	300- 900[b]		
	DIGESTED	6.8-7.2[c]	-200 - -400[d]	100- 900[b]	2500-5000[e]	25-35	65-75
HIGH-RATE ANAEROBIC	RAW			500-2500[a]	300- 900[b]		
	DIGESTED	6.8-7.2[c]	-200 - -400[d]	100- 900[b]	2500-5000[e]	25-35	65-75
AEROBIC	RAW			500-2500[a]	300- 900[b]		
	DIGESTED	6.8-7.2[c]	+100[f]				

a. EVANS, *et al.* (1965), WOOTEN (1957)
b. EVANS, *et al.* (1965).
c. SCHLENZ (1951), CASSEL AND SAWYER (1959), COULTER (1953).
d. GRUNE, *et al.* (1957).
e. McCARTY (1964).
f. DIRASIAN (1968).
g. WPCF (1968), ECKENFELDER AND O'CONNOR (1966).

The ORP values of raw and digested sludge for both the Kailua and Pearl City plants were in the optimum range. The ORP values of raw and digested sludge for the Kaneohe plant are considered to be a little low, but still show strict anaerobic conditions in digestion. The raw sludge ORP for Mililani reflects normal sludge collection practice, but the low ORP on the aerobically digested sludge is somewhat below the best operating point. A still lower ORP value would have serious detrimental affect on the aerobic biological flora required for proper aerobic digestion.

The alkalinity and the volatile acid concentrations of both raw sludge and digested sludge should correspond with pH values. The values of alkalinity and volatile acids for both raw sludge and digested sludge at the three anaerobic digestion plants all compare favorably with results obtained by Evans, *et al.* (1965), as are their respective pH values. Values for Kailua showed alkalinity of 853 mg/l, volatile acids of 543 mg/l, and pH of 5.8 for raw sludge; for Kaneohe alkalinity of 459 mg/l, volatile acids of 1017 mg/l, and pH of 4.7; and for Pearl City alkalinity of 334 mg/l, volatile acids of 606 mg/l, and pH of 6.00.

The above comparisons confirm the fact that low pH values of raw sludge at the three anaerobic digestion plants resulted from relatively high volatile acids concentrations. One reason for the high volatile acids in raw sludge at both Kailua and Kaneohe may be the significant quantities of cesspool mixed liquor collected by pumping trucks and discharged to the treatment plants. This also confirms that it is better to have alkalinity in the usually suggested range of 2500 mg/l to 5000 mg/l for digested sludge to provide a good buffering capacity for the acids produced during liquefaction.

The high volatile acids content of raw sludge at the Pearl City plant is apparently due to the brewery and bakery wastes connected to this sewage system. It was first thought that these wastes caused the difficulties in the pumping of sludge at the plant, indicated by the high concentrations of total solids contained in the first samples obtained at 7 a.m. on sampling days. However, a check of operations showed the high solids problem to be related to the pumping down of the wet well in the lift station ahead of the treatment plant, with subsequent solids build up in the clarifier.

The Mililani plant had an alkalinity of 156 mg/l, volatile acids of 97 mg/l, and a pH of 6.38 for raw sludge. This is about normal for waste activated sludge. But digested sludge at this plant had an alkalinity value of 99 mg/l, a volatile acids content of 256 mg/l, and a low pH value of 5.11. When the volatile acids of 97 mg/l in the raw sludge are compared with that of 256 mg/l in digested sludge, the digestion taking place simulates the first stage of anaerobic digestion. In addition, the ORP values of -109 and +44 mv for raw and digested sludge, respectively, are in the facultative range based on findings by Grune, *et al.* (1957) of a range of +50 to +100 mv to represent the facultative bacteria activity zone. The reason for this condition is apparently due to the blockage of the return sludge chimney in the aeration tank. This yielded septic samples as there was no pumping of the settled sludge in the sedimentation tank before sampling.

Average values for specific resistance to dewatering at the three anaerobic digestion plants are considered to be satisfactory for dewaterability when compared with data given by Coackley (1958), which showed very high results indicating poor dewaterability for digested sludge.

Gas components at the three anaerobic digestion plants are also in the proportion considered representative of satisfactory process operation.

The data relating to conditions of the sludge solids is listed in Table 4. The total solids concentrations for Kailua and Kaneohe are considered adequate, but that for Pearl City is considered to be low for good digestion and that fact is substantiated by the low solids yield in the digested sludge. The raw sludge solids concentration for Mililani is satisfactory for aerobic digestion but the solids yield after digestion is considered low.

The volatile solids content at the Kaneohe and Pearl City plants are within accepted ranges, but that of the raw sludge at Kailua is low, although the content for digested sludge is acceptable. The volatile solids content for the Mililani operation is very high by comparison but probably just reflects the pure domestic nature of the sewage inflow to the plant.

COD results can be used to measure the strength of domestic and industrial waste, but should not be used to determine the exact quantity or organic matter. Since all organic compounds are not amenable to the oxidation conditions in this analytical method, it only yields a general value for comparative purposes. The ratios of COD values to the total solids content for the different plants which indicate the degree of volatile solids reduction are as follows:

PLANT	RAW	DIGESTED
KAILUA	1.00	0.85
KANEOHE	1.11	0.82
PEARL CITY	1.46	0.82
MILILANI	1.20	0.52

Both Kaneohe and Pearl City showed the best solids reduction, Mililani was next, and Kailua had the least reduction.

TABLE 4. SOLIDS AND ORGANIC DATA.

PLANT	SAMPLE	TOTAL SOLIDS PERCENT	VOLATILE SOLIDS PERCENT	VOLATILE SOLIDS REDUCTION PERCENT	SPECIFIC RESISTANCE TO DEWATERING r sec^2/gr	COD mg/l
KAILUA	RAW	3.36	64	30	2.15×10^{10}	33570
	DIGESTED	4.85	57		0.63×10^{10}	39540
KANEOHE	RAW	4.37	78	64	2.03×10^{10}	48320
	DIGESTED	6.01	56		1.41×10^{10}	49230
PEARL CITY	RAW	2.32	77	64	5.38×10^{10}	33870
	DIGESTED	1.05	55		2.96×10^{10}	8610
MILILANI	RAW	1.15	81	49	3.77×10^{10}	13840
	DIGESTED	1.32	70		8.74×10^{10}	6900
REPORTED PRACTICE						
CONVENTIONAL ANAEROBIC	RAW	3.7- 9.4[a]	60-80[b]			
	DIGESTED	3.5- 4[c]	40-65[d]	60-75[e]	$1.2 - 2.6 \times 10^{10}$[f]	
HIGH-RATE ANAEROBIC	RAW	2.8-10.2[g]	60-80[b]			
	DIGESTED	3.5- 9.6[h]	40-65[d]	60-75[e]	$1.2 - 2.6 \times 10^{10}$[f]	
AEROBIC	RAW	1.0[i]	48.8[j]			
	DIGESTED	2.76[i]	39.5[j]	40-60[k]	$0.6 - 3.8 \times 10^{10}$[f]	

a. WPCF (1968).
b. WPCF (1968), TORPEY (1954), BABBITT AND BAUMANN (1958).
c. BURD (1968).
d. BURD (1968), BABBITT AND BAUMANN (1958), ZACK (1950).
e. BURD (1968).
f. COACKLEY (1958).
g. TORPEY (1954).
h. DREIER (1963).
i. LOEHR (1965).
j. TORPEY (1954).
k. LOEHR (1965).
l. WPCF (1968), LOEHR (1965).

The volatile solids reduction values were determined by using the solids reduction charts shown in Figures 6 and 7 for anaerobic and aerobic digester systems, respectively. Overall, the volatile solids reduction obtained at the four plants was less than optimum. Although the Kailua plant had the lowest reduction, the digested sludge had no odor, a black color, and a satisfactory dewaterability. Thus, effective sludge digestion may be obtained even with low solids reductions.

The cation content of the sludges is listed in Table 5. Chloride values shown reflect the chlorinity of the carriage water and groundwater infiltration into the sewerage systems for the different plant locations. A review of the chloride concentrations found at the four plants shows that only that for raw sludge and digested sludge at Kailua plant seems high with values between 2000 to 3000 mg/l. This range is reported to have no influence on good digestion, but it may be a little inhibitory as shown by the low volatile solids reduction (30 percent) at this plant. The values of the chloride content at the remaining plants have no influence on digestion.

TABLE 5. IONIC CONTENT.

PLANT	SAMPLE	CHLORIDE mg/l	SODIUM mg/l	CALCIUM mg/l
KAILUA	RAW	2620	945	135
	DIGESTED	2415	935	195
KANEOHE	RAW	1505	325	85
	DIGESTED	1020	230	45
PEARL CITY	RAW	645	130	20
	DIGESTED	840	170	40
MILILANI	RAW	149	70	10
	DIGESTED	125	80	20
REPORTED PRACTICE	NO EFFECT	<5000[a]	<100[b]	<100[b]
	STIMULATORY	<5000[a]	100-200[b]	100-200[b]
	INHIBITORY OR TOXIC	<5000[a]	>3500[b]	>2500[b]

a. ZACK (1950).
b. HOLLIS (1961).

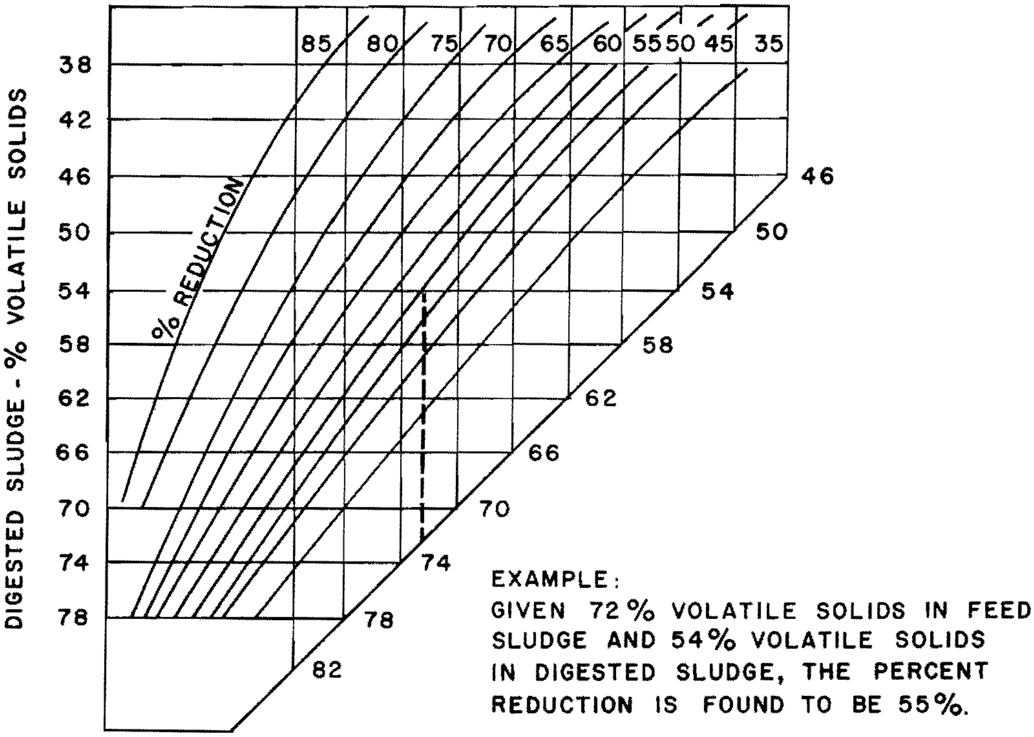

FIGURE 6. VOLATILE SOLIDS REDUCTION CHART (5) (WATER POLLUTION CONTROL FEDERATION, 1968).

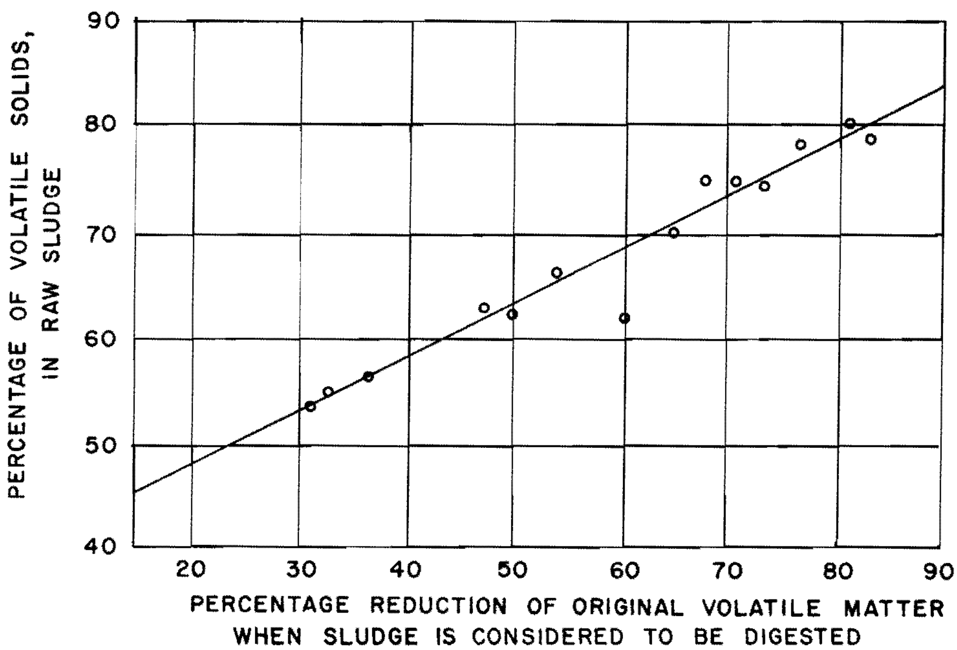

FIGURE 7. REDUCTION IN VOLATILE MATTER BY DIGESTION (5).

The sodium content at the Kailua, Kaneohe, and Mililani plants is in a range that does not inhibit digestion, but that at the Pearl City plant is in the stimulatory range and should assist the digestion process.

The calcium content at Kailua is in the stimulatory range and should assist the digestion process. No effect from calcium should be expected at any of the other plants.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this study the following conclusions can be made:

1. All plants studied have not achieved their optimum potential sludge treatment efficiency.
2. All plants do not run sufficient routine tests for complete surveillance for optimum operation.
3. The three anaerobic treatment plants were fairly well operated considering the minimum of information available to the operators
4. The Mililani plant is not considered to be operating in a true aerobic digestion range, but rather in a facultative digestion range. This plant was not operated in the optimum range due to the lack of good recirculation of return sludge.
5. The very low volatile solids reduction at Kailua plant is apparently due to the conditions of the raw sludge feed and chloride inhibition.
6. The very low average pH value of 4.7 for raw sludge at Kaneohe plant is apparently due to the discharge of cesspool liquor into the plant.
7. The dewaterability of digested sludge at three aerobic digestion plants is satisfactory.
8. The hydraulic detention and solids retention times at the four plants are adequate for good digestion.
9. The loading rates at Kailua and Kaneohe are suitable for good digestion but those at Pearl City and Mililani are low.

Based on the findings of this study the following recommendations are made for future operations:

1. Routine tests should be performed to provide data to adjust the plant operation to achieve optimum treatment according to the recommended values for those parameters which control digestion.
2. Recommended daily tests to be performed by operators are pH, ORP, total solids content, and volatile solids content. Weekly tests of chemical oxygen demand, alkalinity, volatile acids, and specific resistance to dewatering are recommended to be performed by laboratory analysts. Determination of gas components by the operators is also recommended at the three anaerobic treatment plants.
3. Liming is recommended when cesspool liquor is being discharged into the Kailua or the Kaneohe plants, if continued acid conditions result in the feed sludge.
4. The digester temperature should be raised to 95°F at the Pearl City plant to insure optimum digestion.
5. Installation of an automatic pressure air diffuser in the return sludge chimney is recommended to improve the recirculation of return sludge at the Mililani plant and aerobic conditions should be maintained at all times in the digester.

ACKNOWLEDGEMENTS

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The counsel and guidance of N.C. Burbank, Jr. and L. Stephen Lau are gratefully acknowledged as is the assistance of James S. Honke in analytical work and preparation of original drawings.

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