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AEROBIC STABILIZATION OF WASTE ACTIVATED SLUDGE
An Experimental Investigation

Municipal Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

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AEROBIC STABILIZATION OF WASTE ACTIVATED SLUDGE

An Experimental Investigation

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise, and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The Municipal Environmental Research Laboratory contributes to this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

The research reported here was performed for the Ultimate Disposal Section of the Wastewater Research Division to determine the effects of different operational parameters on and develop design criteria for the aerobic digestion process. In addition, various benefits were demonstrated on a pilot plant scale for a pure oxygen digestion process. Large cost savings have been realized at Metro Denver with aerobic digestion of their waste activated sludge.

ACKNOWLEDGEMENTS

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The investigation of the full scale aerobic digestion system was carried out by the staff of the Metropolitan Denver Sewage Disposal District No. 1. Mr. John Puntenney was the Project Director; Dr. David Cohen was Project Coordinator. In particular, the following individuals contributed significantly to the implementation of the project:

Mr. William Martin - Field Supervisor

Mr. Harry Harada - Laboratory Supervision

Ms. Mary Ann Tavery - Laboratory Analysis and Coordination

Mr. Steve Pearlman - Laboratory Analysis and Coordination

Mr. William Broderick - Graphics

Mrs. Pam Stover - Stenographic Support

The pure oxygen pilot plant phase of the project was jointly carried out by Metro staff and F.M.C. Corporation, Marox Diffusion Systems, Englewood, Colorado. The advice and assistance of the following individuals are particularly acknowledged: Mr. Richard B. Weber - Subcontract Director, Mr. Donald G. Fullerton - Field Coordinator for the oxygen system and Mr. Gordon Drew - Field Engineer.

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FIGURES (continued)

SUMMARY AND CONCLUSIONS

Metro Denver Sewage Disposal District No. 1 (Metro)'s aerobic digestion system consisted of four converted secondary aerators (8 million gallons) using diffused air. The digesters were fed waste activated sludge (WAS) and were operated in a plug flow mode. Aerobic digestion performance averaged 32.0% VSS reduced with a minimum of 11.2% during low temperature high loading conditions and a maximum of 47.2% during warm weather, low loading conditions. Based on a 13 month evaluation of the diffused air digester performance, it was determined that

> a well stabilized sludge should have the following characteristics: a) temperature standardized specific respiration rate K_{20} of less than 5.0 mg/hr/g VSS, b) reduction in volatile fraction between WAS influent and digested effluent greater than 6%, c) NO_3-N/NH_4-N greater than 1.0 in effluent, d) effluent/influent conductivity ratio greater than 1.5, e) effluent/influent alkalinity ratio less than 0.60, f) pH reduction between influent and effluent greater than 0.3 units, g) a supernatant quality with TSS concentration less than 30 mg/l, BOD less than 100 mg/l and NH_4-N less than 100 mg/l. Best digestion performance was found to coincide with rotifers comprising the majority of the invertebrate biomass on a volumetric standard unit basis (VSU).

In cold climates with biomass less than 20^{o}C, sludge loading must be corrected for cold temperature inhibition of metabolic activity. A new design parameter in units of degree-days (SRT x temperature ^{o}C) is suggested as a practical approach to digester performance predictability. A temperature-time factor in excess of 150 degree-days should be maintained to ensure a VSS reduction rate of greater than 40%. If the biomass is subjected to cold temperature shock (i.e. 5^{o}C or greater drop in 5 days), the temperature-time factor should be increased to 250 degree-days. Nitrification was inhibited in the diffused air digester when shock chilling occurred.

The best solid/liquid separation performance was obtained at loadings between 0.8 - 1.28 kg VSS/m^3/day (0.05 - 0.08 lb VSS/ft^3/day). Because of low sludge subsidence rates it was impossible to maintain constant supernatant removal. The batch approach of shutting off air flow temporarily to create a quiescent settling zone frequently led to anaerobiosis, denitrification, and floating sludge. Clogging of fine bubble diffusers was also increased when batch supernating was attempted.

If the digested sludge is to be applied to land, the concept "stabilization" must be operationally defined in relation to odor potential. If a mixture of anaerobically and aerobically digested sludges are applied to land, objectionable odors may result unless the volatile fraction of both sludges is less than 60%.

For aerobically digested sludge with SRT between 3 and 13 days, sand bed drainability on a volumetric basis was three times faster than well digested anaerobic sludge. On a mass basis however, the anaerobic sludge drained 2.5 times faster than aerobically digested sludge. Dewaterability of the aerobically digested sludge as determined by specific resistance (of the aerobically digested sludge) was not significantly different than that of waste activated sludge prior to digestion. For an equivalent chemical cost, however, better vacuum filter leaf test performance was obtained with the aerobically digested sludge compared with undigested sludge. Polymer demand for air flotation of the digested sludge increased in direct proportion to increasing SRT because of increased particle breakdown creating additional surface area for polymer attachment.

Air supply required to maintain 1.0 mg/l dissolved oxygen averaged 0.5 l/sec/m^3 (30 cfm/1000 ft^3) with a range of 0.3 to 0.75 l/sec/m^3 (18 to 45 cfm/1000 ft^3), the minimum occurring during cold weather. Specific oxygen uptake rates K_r averaged 7.1 mg/hr/g VSS ranging from 3.4 to 11.1. Oxygen transfer efficiency averaged 10% ranging between 5% during warm weather to 19% during cold weather.

A comparison of operations and maintenance costs for the diffused air aerobic digestion system with costs of conventional sludge disposal methods at Metro indicated a benefit/cost ratio of 3.5:1 and a cumulative savings in sludge disposal costs in excess of $1,000,000 for the years 1970-1974.

Concurrent with evaluation of the diffused air aerobic digestion system, a parallel investigation of pure oxygen digestion of concentrated waste activated sludge (5% TS) using the open tank fine bubble MAROX system was conducted. The diffused air system was not capable of satisfying the oxygen respiration requirements of a polymer floated waste activated sludge. The high oxygen demand (greater than 200 mg/l/hr) was consistently satisfied with the oxygen system. Two different pure oxygen diffusion devices were investigated, the slot type Fixed Action Diffuser (FAD) which had a tendency to plug with screened influent and a Rotating Active Diffuser (RAD) which required no screening. Aerobic digestion performance with the FAD averaged 42.7% VSS reduced with a minimum of 38.8% at the highest loading rate of 6.94 kg VSS/m^3/day (0.433 lb VSS/ft^3/day). Aerobic digestion performance with the RAD averaged 33.7% VSS reduced at a loading range between 6.88 and 9.62 kg VSS/m^3/day (0.43 to 0.60 lb VSS/ft^3/day).

Oxygen uptake (R_r) averaged 176 mg/l/hr with a maximum of 562 mg/l/hr. R_r during the RAD test period averaged 218 mg/l/hr with a maximum of 453 mg/l/hr. Specific O_2 uptake K_r averaged 6.0 mg/hr/g VSS with the FAD and 7.3 mg/hr/g VSS with the RAD.

During both the FAD and the RAD test periods, a significant temperature increase occurred in the biomass compared with surrounding atmosphere and was directly proportional to the organic loading rate. Temperature differential increased from 1°C at 1.33 kg VSS/m^3/day (0.083 lb VSS/ft^3/day) to 23°C at 9.63 kg VSS/m^3/day (0.6 lb VSS/ft^3/day).

The higher sludge concentration and temperatures in the pure oxygen system resulted in declining ecological diversity of the digester biomass with bacteria predominating and stalked ciliates and rotifers absent.

During the pure oxygen batch tests, the total VSS digestion rate coefficient k equalled 0.07, while the readily biodegradable VSS rate coefficient equalled 0.27. No correlation was observed between rate of digestion and dissolved oxygen concentration above a minimum of 1.0 mg/l. No solid-liquid separation was observed in the polymer thickened sludge, before or after digestion.

At loading rates greater than 2.4 kg VSS/m^3/day (0.15 lb VSS/ft^3/day), the VSS reduction rate was significantly greater with the pure oxygen flow-through system. At lower loading rates, VSS reduction rates were equal or greater in the diffused air system. The diffused air system required 15 kg O_2/kg VSS reduced compared with 2.3 kg O_2/kg VSS for the FAD and 1.4 kg O_2/kg VSS for the best performance with the RAD. The temperature-time factor (^{o}C x SRT) for predicting digester performance was found to be valid for the pure oxygen system as well.

Advantages of pure oxygen digestion compared with diffused air digestion include (a) ability to digest thickened waste activated sludge having high oxygen uptake demand, (b) reduced space requirements, (c) reduced gas flow requirements, (d) exothermic waste heat production which can be utilized to accelerate digestion reaction rates in the mesophilic temperature range.

Future research in this area should be directed towards investigation of pure oxygen thermophilic digestion of thickened waste activated sludge. Conservation of the waste heat produced by insulating the reaction vessel could raise the biomass temperatures to the 50-65^{o}C range. Potential benefits of thermophilic aerobic digestion include greater degree of volatile solids fraction reduction, reduced detention time requirements and increased pathogen destruction.

INTRODUCTION

The purpose of this research project was to provide information on the aerobic stabilization process by studying the effects of diffused air and high purity oxygen on dilute and thickened waste activated sludges both on a plant and pilot scale basis. Plant scale testing involved the diffused air aerobic stabilization of dilute waste activated sludge (0.5 - 1% total solids) while pilot scale testing involved pure oxygen stabilization of thickened sludge (4 - 5% total solids).

Scope of the Study

Variables investigated in relation to aerobic stabilization performance included:

1. Time of stabilization.
2. Volatile solids loading.
3. Temperature.
4. Amount of oxygen required per unit volatile solids reduced.
5. Dissolved oxygen concentration.
6. Oxygen uptake rates.
7. Digested sludge thickening.
8. Settled sludge supernatant quality.
9. Odor levels.
10. Dewaterability.
11. Other physical, chemical and microbiological characteristics.

In addition, existing plant records in the solids handling unit processes were utilized to enable correlation of changes in aerodigestion operation with changes in other solids handling unit processes, e.g. dissolved air flotation and vacuum filtration. Finally, information which indicated economic promise on a pilot scale was used as a basis for recommending plant scale process modification for the Metro Denver Sewage Disposal District No. 1 (Metro).

Early Metro Operational Experience

Metro, since its inception in 1966, has been confronted with the problem of handling and disposing of waste activated sludge (WAS). Original design for the plant envisaged a WAS/total sludge ratio of 0.50, whereas by 1970 the WAS/total sludge ratio was 0.65. The inordinate proportion of difficult to dewater waste activated sludge compounded the total sludge disposal effort. Massive doses of conditioning chemicals were required for vacuum filter dewatering, which in turn adversely affected the operation and maintenance of the flash dryer-incinerator equipment. Further, insufficient incineration capacity resulted in sludge accumulation and subsequent deterioration in secondary removal efficiencies. As a consequence of these difficulties, incineration was abandoned in 1971 in favor of land spreading and incorporation of vacuum filter cake.

The sludge disposal problem was subjected to a detailed investigation with particular emphasis on reduction of sludge volume. Metro staff initiated a number of lab and field research projects which included:

a) Preflocculation of primary influent flow using anionic polymers and ferric chloride.

b) Pumping of Metro waste activated sludge to a neighboring primary treatment plant for anaerobic sludge digestion.

c) Aerobic digestion of waste activated sludge using diffused air.

The first two projects were not pursued further either because of excessive costs or capacity limitations. The aerobic digestion project however showed promise of economic mass reduction through the use of excess aerator and blower capacity. Modification of the existing secondary facilities to aerobic digesters required only installation of "v" notch weirs to monitor return sludge flows to the aerobic digesters. Existing drain piping was used to transfer the digested sludge to air flotation units for further concentration.

In June 1970 two previously empty secondary aeration basins were converted to aerobic digesters. Strict monitoring of flows and sampling of influent and effluent enabled a solids material balance to be calculated. No additional compressor horsepower was required for aerobic digestion during 1970. The compressed air 37800 l/sec (80,000 cfm) was redistributed more equitably between the secondary aerators and the aerobic digesters to ensure at least 1.0 mg/l of dissolved oxygen in all basins.

The immediate relief which these modifications provided in sludge handling and disposal convinced Metro staff of both the feasibility and desirability of subjecting all the waste activated sludge to aerobic digestion. Consequently, in August 1970, two additional basins which had previously been used as preaeration and grease skimming tanks were drained, and converted to aerobic digesters. This provided each quadrant of the secondary facility with two aeration basins 15140 m^3 (4.0 mil gal), one aerobic digester 7570 m^3 (2.0 mil gal) and three secondary clarifiers 11350 m^3 (3.0 mil gal). (Figure 1).

During 1971, (the first full year of plant scale aerobic digestion) an average daily loading to the digesters of 48 tons TSS and an average digested sludge loading to the air flotation units of 31 tons TSS represented a 35% reduction in volatile suspended solids. Solids loadings averaged 1.44 kg VSS/m^3/day (0.09 lb VSS/ft^3/day), while air consumption averaged 0.667 l/sec/m^3 of aeration capacity (40 cfm/1000 ft^3).

Aerobic digestion operations and maintenance costs averaged $15 to $20 per ton, compared with a total sludge handling and disposal cost of $50 per ton by conventional methods of vacuum filtration, incineration or land disposal. Sludge disposal costs were therefore reduced in 1971 by approximately $200,000, by converting one-third of the activated sludge capacity to aerobic digesters.

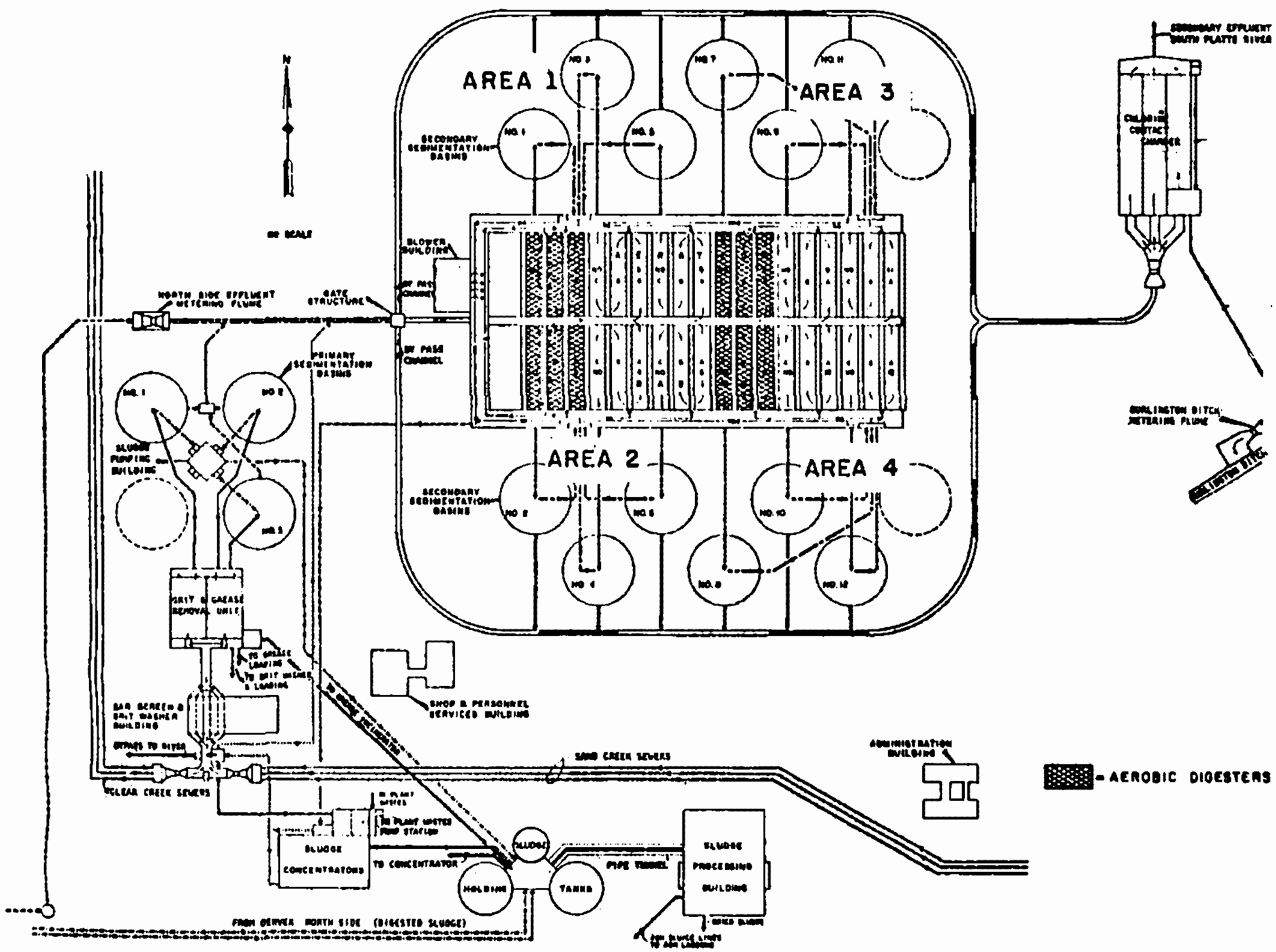


Fig. 1. Schematic flow diagram of Metro Denver Sewage Treatment Plant

Open Tank Oxygenation Research

As hydraulic and organic loading to Metro's facilities increased, part of the secondary aeration capacity that was used for digestion during 1970-1972 had to be converted back to secondary aeration basins. This fact led to a joint research and development effort between Metro and Martin Marietta Company to investigate the potential for using pure oxygen in the aerobic stabilization process. Preliminary research data indicated that high oxygen transfer efficiencies could be achieved by applying a unique fine bubble oxygen diffuser in an open tank system. Although Metro's air diffusion system could not support the high oxygen demand of thickened waste activated sludge (4-5% TS), pure oxygen fine bubble diffusion could meet this demand. It was immediately evident that the benefits of aerobic digestion could continue to be obtained in much smaller space, provided that this digestion was accomplished after thickening of the waste activated sludge.

The investigation of diffused air and pure oxygen aerobic digestion of waste activated sludge reported here began in August 1972. The plant scale diffused air aerobic digestion phase was completed by August 31, 1973. The pure oxygen digestion phase began on November 1, 1972 and continued until May 5, 1974.

Plant Scale Testing

The plant scale diffused air tests were conducted in one of the 7570 m^3 (2 mil gal) aerobic digesters that were modified for this purpose in 1970. The test digester (No. 7) was isolated in such a way as to provide for a wide range of sludge loading rates. Each operational mode was held at a constant loading rate for thirty days with one week intervals between modes during which loadings were adjusted to the new rate.

By operating the digester at the same loading rate at different seasons of the year, the effect of temperature on the stabilization process was evaluated. Solids loading rates were controlled within the sludge retention time range compatible with Metro's solids handling needs and capabilities. Essentially, five different loading rates were applied during the 13 month period. They ranged from a minimum of 0.417 to a maximum of 3.0 kg VSS/m^3/day (0.026 to 0.187 lb VSS/ft^3/day) Monthly temperatures ranged from 15.8°C during February - April to 28.7°C during August - September. Sludge retention times (SRT) ranged between 3.0 and 29.8 days. Due to limitations diffused air oxygen transfer capabilities, it was not possible to investigate a wide range of dissolved oxygen concentrations. A minimum DO of 1.0 mg/l was however maintained throughout the plant scale test period.

Because of flood conditions at the plant site during May 1973, the data for this period were non-representative of normal volatile solids concentrations. Monitoring of the plant scale air system was therefore continued until the end of August 1973, to obtain twelve full months of representative data.

Oxygen Pilot Plant Testing

The oxygen investigation was carried out in three stages. Stage one included a series of five batch tests for evaluation of diffuser hardware and system performance. Data obtained were also used in the operation and control of subsequent flow-through tests. Both undigested and diffused air digested WAS were used in these batch tests after air flotation concentration to 4-5% TS. Stage two of the oxygen investigation consisted of a flow-through system (Figure 2) using the slot type fixed active diffuser (FAD) for determining the effects of loading rates on system performance. During the five phases of stage two, solids loadings ranged from 1.33 to 6.94 kg VSS/m^3/day (0.083 to 0.433 lb VSS/ft^3/day). Stage three duplicated the flow-through system of stage two but used a rotating active diffuser (RAD) in a single tank. The loading rates were 6.89 to 9.61 kg VSS/m^3/day (0.43 to 0.60 lb VSS/ft^3/day).

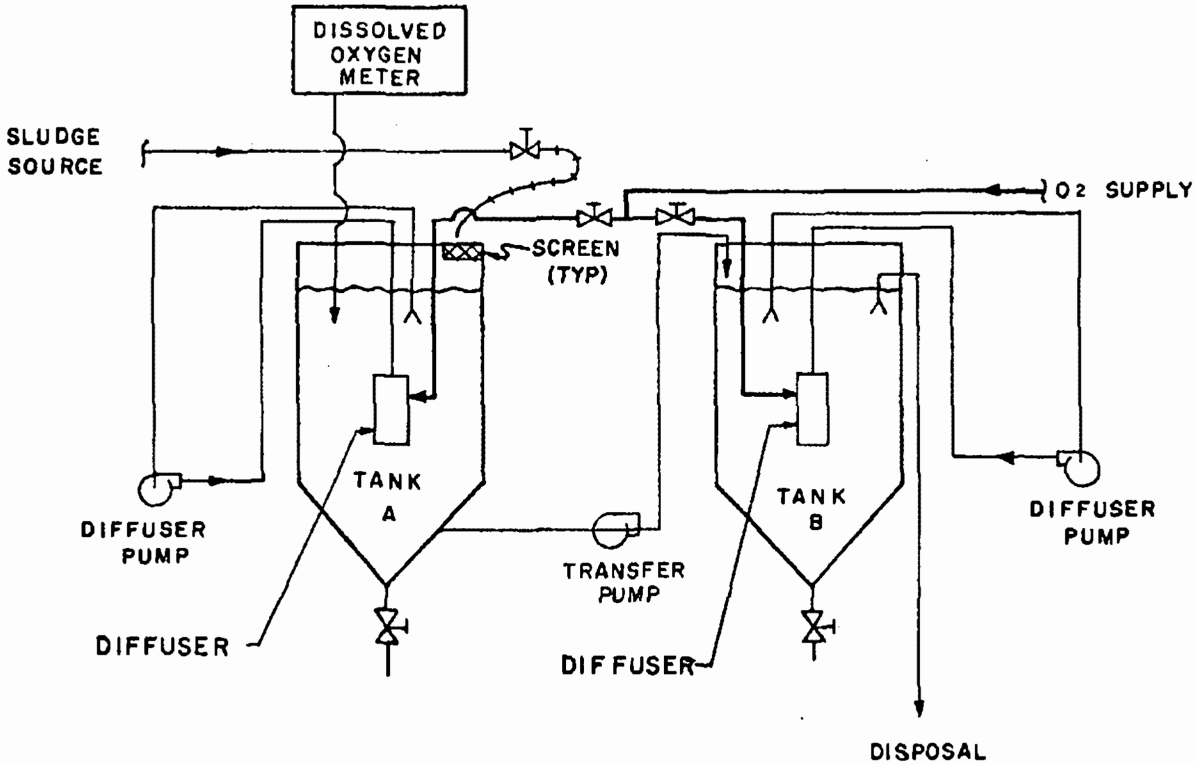


Fig. 2. High purity oxygen flow through pilot plant with fixed active diffuser

MATERIALS AND METHODS

Metro Diffused Air System

The plant scale diffused air system employed existing aeration equipment consisting of precision tube diffusers. The precision tube diffusers provide an average bubble diameter of approximately 2 - 5 mm. The only innovation used in the plant scale study was the shutting off of diffused air in the third and last pass of the aeration basin once a day to allow for solids/liquid separation. This action was followed by decanting of clear supernatant to the secondary influent. Supernatant transfer was accomplished with portable 31.5 l/sec (500 gpm) pumps. A water level indicator was installed at the head of "C" pass in No. 7 aerobic digester (Figure 1) to enable accurate solids and hydraulic balances to be calculated before and after decanting.

Oxygen System

The oxygen system utilized a unique method for dissolution of oxygen in the liquid sludge. The oxygen diffusion hardware is configured so that oxygen bubbles that are formed from a multiplicity of very small orifices (4 micron or less) are sheared from the forming surface by a high velocity sludge stream 305 cm/sec - (10 ft/sec) to develop bubble sizes that average 50 to 100 micron in diameter. The sludge stream flows perpendicular to the gas emitting surface and is pumped by an externally mounted pump recycling the tank contents. The sludge flow through each of three vertical slots of the diffuser used in this project provides the necessary mixing requirements to circulate the tank contents (Figure 4). This particular hardware (slot type) is identified as the fixed active diffuser (FAD). The slot gap for sludge of this solids concentration was 0.203 to 0.254 cm (0.080 to 0.100 inch) to maintain the proper flow for both bubble shear requirements and tank mixing. The slot width required prescreening of the tank influent sludge through 0.317 cm (1/8 inch) mesh screen. Two existing Moyno positive displacement pumps were used to recycle the sludge through the slot diffusers, one for each of the sludge digestion tanks.

The oxygen diffuser (FAD) used during the first stage (batch tests) and the second stage (flow-through tests) had three vertical slots 30.5 cm (12 inches) long mounted on a water box 10 cm (4 inches) square and approximately 43.2 cm (17 inches) long. The pumped sludge entered the water box at the top through a 5.08 cm diameter (2 inch diameter) opening. The diffuser was attached to a flexible hose that was connected to the sludge manifold at the top of the tank. A gas manifold around the top of the diffuser distributed oxygen to each of the 6 gas bars.

The importance of this small bubble size is shown in Figure 3 which illustrates the maximum allowable bubble size at certain depths of unsaturated tap water to obtain 100% dissolution of that bubble. As an example, a bubble of 100 microns diameter would require a water depth of at least 1.22 meters (4 feet) to obtain 100% dissolution before reaching the air/water interface. Figure 3 was a theoretical line later verified in clean water testing.

During the third stage of the oxygen test program, an experimental gas transfer device developed by FMC - Marox systems became available. This device, called a rotating active diffuser (RAD), employed the same shear principle for small bubble development used in the FAD. While the shear for the FAD was obtained by recirculation of sludge through a narrow slot between the gas bars, the RAD shear was accomplished by revolving gas bars mounted on a cylindrical drum through the sludge at a peripheral velocity of approximately 6.1 m/sec (20 ft/sec). A propeller mounted beneath the gas diffusion drum providedthe mixing requirement for the tank contents. The major advantage of the RAD compared to the FAD is the former device does not require prescreening since the sludge is not required to pass through any narrow passages. (Figure 5). The pilot scale system included two 6.8 m^3 (1800 gallon) tanks that were adapted for these tests. Piping, pumps and other accessories were added to accomplish the necessary sludge transfer into and out of the system.

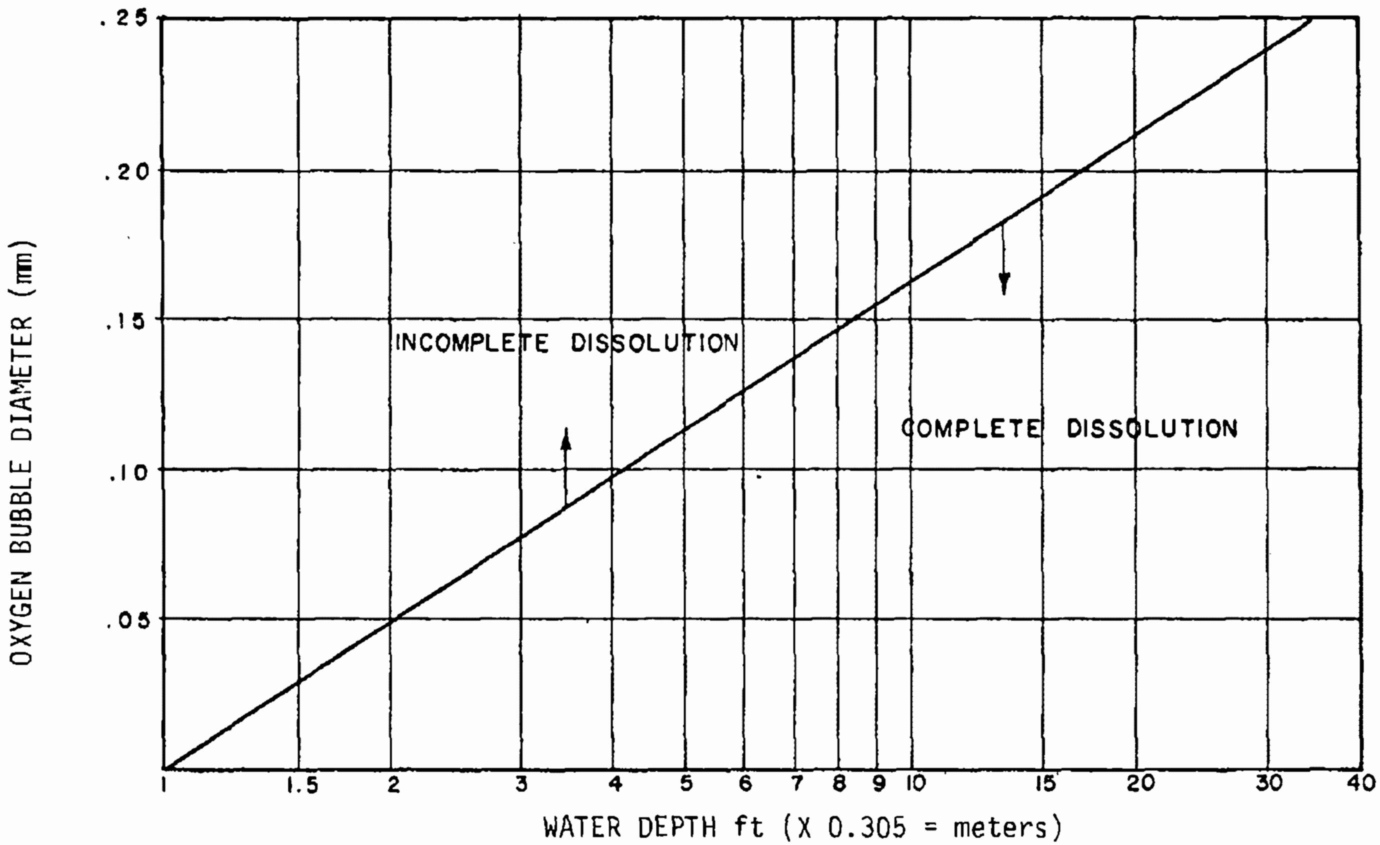


Fig. 3. Oxygen bubble diameter versus water depth required for 100% dissolution

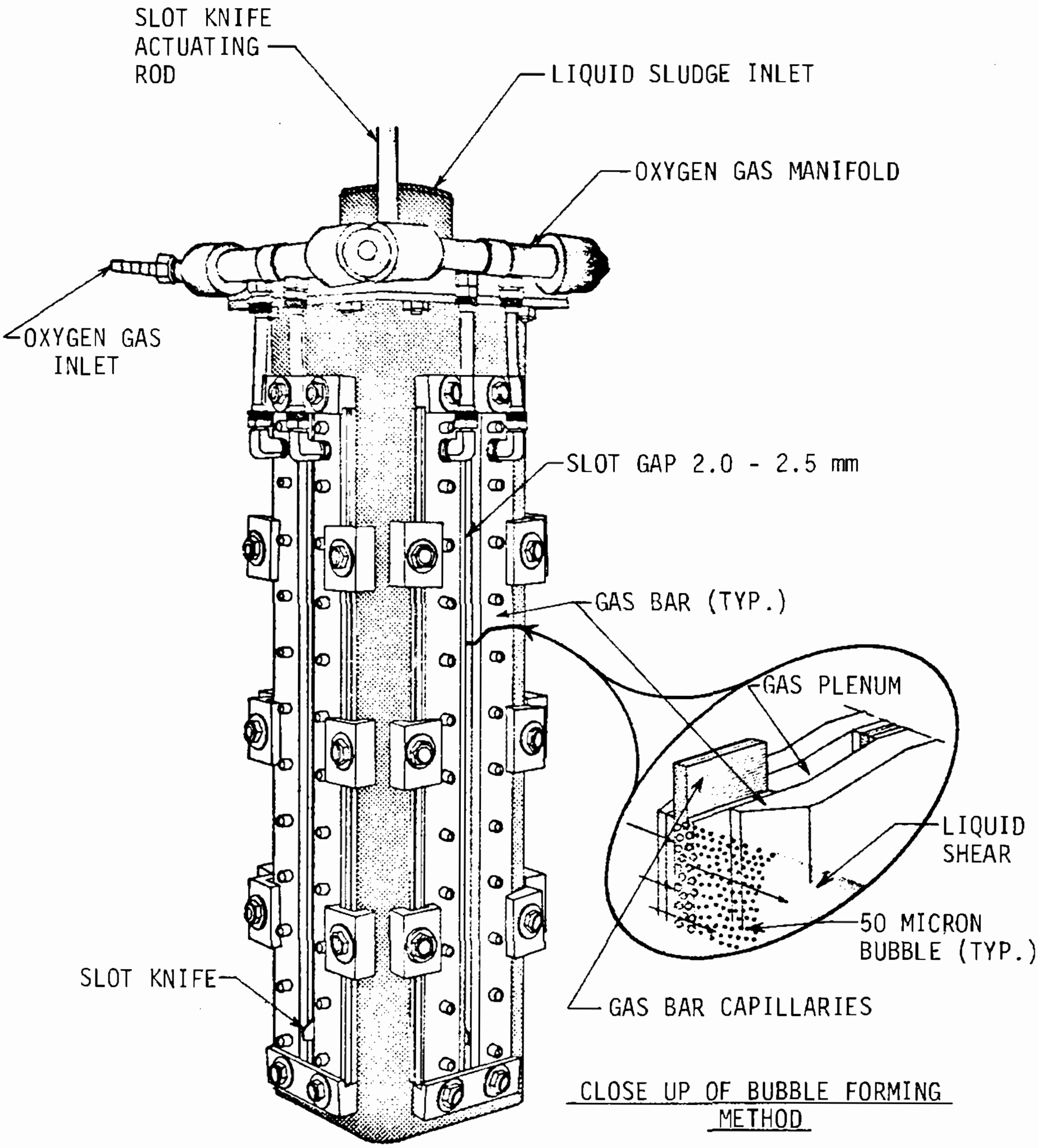


Fig. 4. Fixed active diffuser (FAD) showing bubble shear method

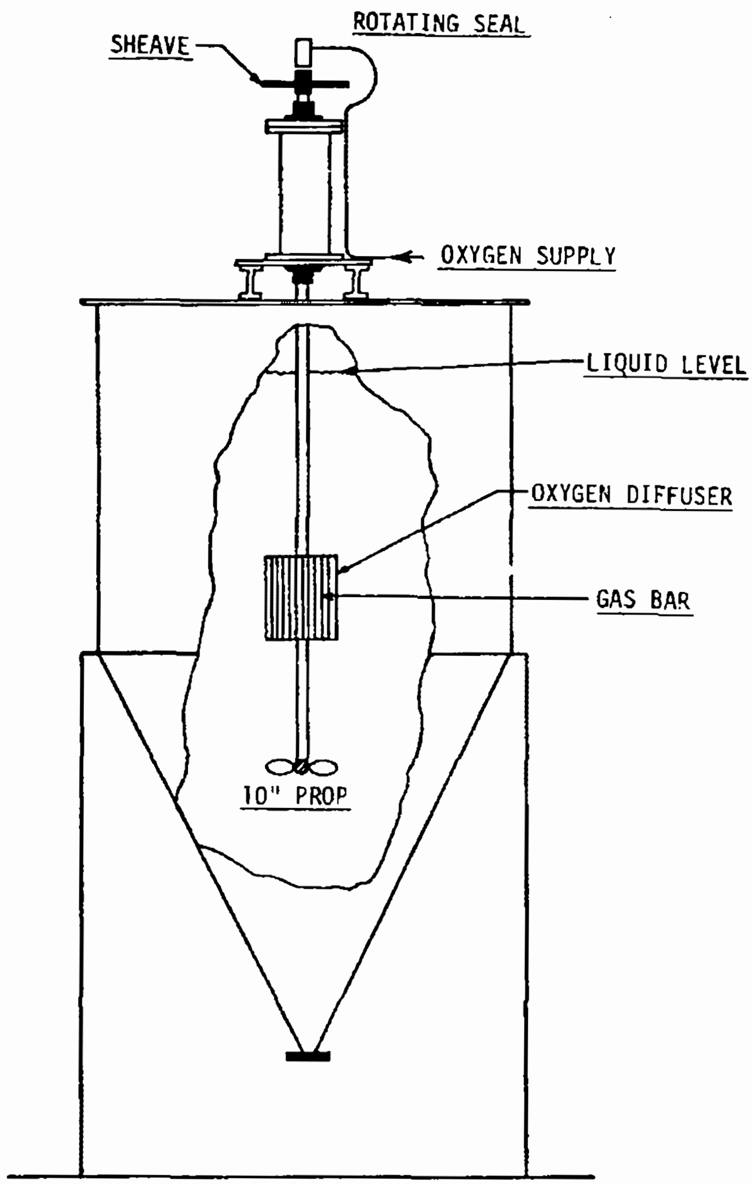


Fig. 5. High purity oxygen pilot plant with experimental rotating active diffuser

The stage one batch test program in a single tank used a combination of one to three FADs, each with four slots. Valving capability was provided to remove any diffuser from the sludge manifold at the top of the tank. During this stage, it was determined that one - three slot diffuser would provide adequate oxygen dissolution and mixing for the next stage of testing. During stage one, second batch test, a serious foaming problem was experienced. For this reason a spray system was installed using a separate recycle pump and spray nozzles to eliminate this avenue of solids loss. A second foam suppression system was installed in "B" tank before start up of stage two testing.

During stage one and the first two phases of stage two, slot cleaning of the FAD was remotely accomplished by knife blades in the slots moving up and down manually to clear the accumulated debris. For phases three to five of stage two, a valving arrangement was installed to provide backflushing of the diffuser slots to prevent debris accumulation. The second tank "B" provided separation between undigested and digested solids so that short circuiting would be minimized.

Transfer of the material from "A" tank to "B" was accomplished by one of the spray pumps, since gravity flow could not be maintained with the concentrated material. Sludge loadings were sequential with the operator first wasting from "B" tank, then transferring an equivalent volume from "A" tank to "B" tank, followed by loading of "A" tank with concentrated feed sludge. Digested sludge was collected in a calibrated 55 gallon drum for material balance purposes. When high VSS loadings were required, the removal of digested sludge had to proceed in several steps because of the requirement to maintain a minimum liquid level above the suction to the Moyno pumps. Thirty centimeters (1.0 ft) of freeboard were provided in each of the two tanks for a net volume of 6.52 m^3 (1,722 gallons) per tank.

A core sampling method was developed whereby the exterior surface of the sampler was wiped during removal from the tank to obtain a representative composite sample for lab analysis. While automatic dissolved oxygen sensor equipment was available during part of the test program, it was determined that the DO sensor used did not provide an adequate signal to control the system. This necessitated manual DO control.

EXPERIMENTAL RESULTS - DIFFUSED AIR SYSTEM

Field Data

Figure 1 shows the aeration basins in each of the four quadrants that were converted to aerobic digesters. Figure 6 is a simplified flow diagram depicting how the aerobic digestion unit process fits into the total solids handling and disposal scheme. The aerobically digested sludge is blended with raw primary and anaerobically digested sludges, and the mixture is vacuum filtered prior to land disposal. A summary of the average monthly field data for the test period is presented in Table 1.

Figure 7 depicts the average monthly temperature (^{o}C) of the biomass undergoing aerobic stabilization, as well as the maximum and minimum monthly values. The annual average temperature was 22.2^{o}C with an observed range of 11.5 - 32.2^{o}C. Figure 8 compares average monthly dissolved oxygen concentrations (mg/l) with specific oxygen uptake rates K_r (mg O_2/hr/g VSS). Dissolved oxygen concentrations ranged between 1.0 and 3.5 mg/l averaging 1.9 mg/l, while oxygen uptake rates ranged between 3.5 and 11.1 averaging 7.1 mg/hr/g VSS for the entire test period. The K_r values are higher than the 3 - 4 mg/hr/g VSS reported in the literature as "normal" for the endogenous respiration phase,[1] and may be accounted for by re-synthesis O_2 requirements. The data show that oxygen uptake is higher at the higher temperatures and the coefficient of correlation was +0.63. No meaningful correlation was observed between O_2 uptake and nitrification rates. As SRT in the digester increased beyond 15 days, K_r declined to its lowest level of less than 5.0 mg/hr/g VSS.

When K_r was temperature corrected to 20^{o}C, the relationship between oxygen uptake and temperature changed from a positive to a negative correlation. Using the equation:

$$\log {}^{R}r_{(20)} = \log {}^{R}r_{(t)} - .0315\,\Delta t$$

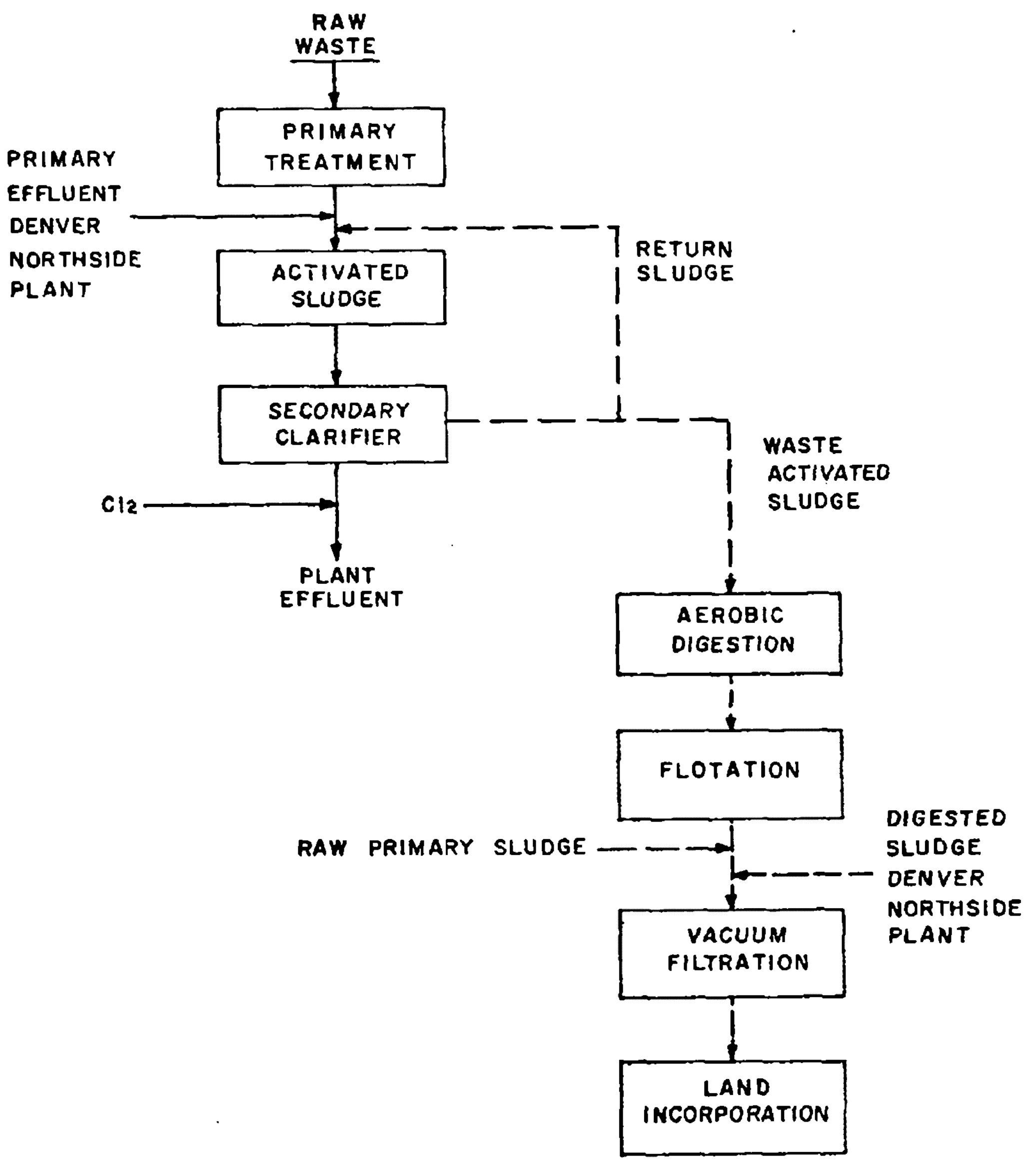


Fig. 6. Simplified plant flow diagram of Metro Denver Sewage Treatment Plant

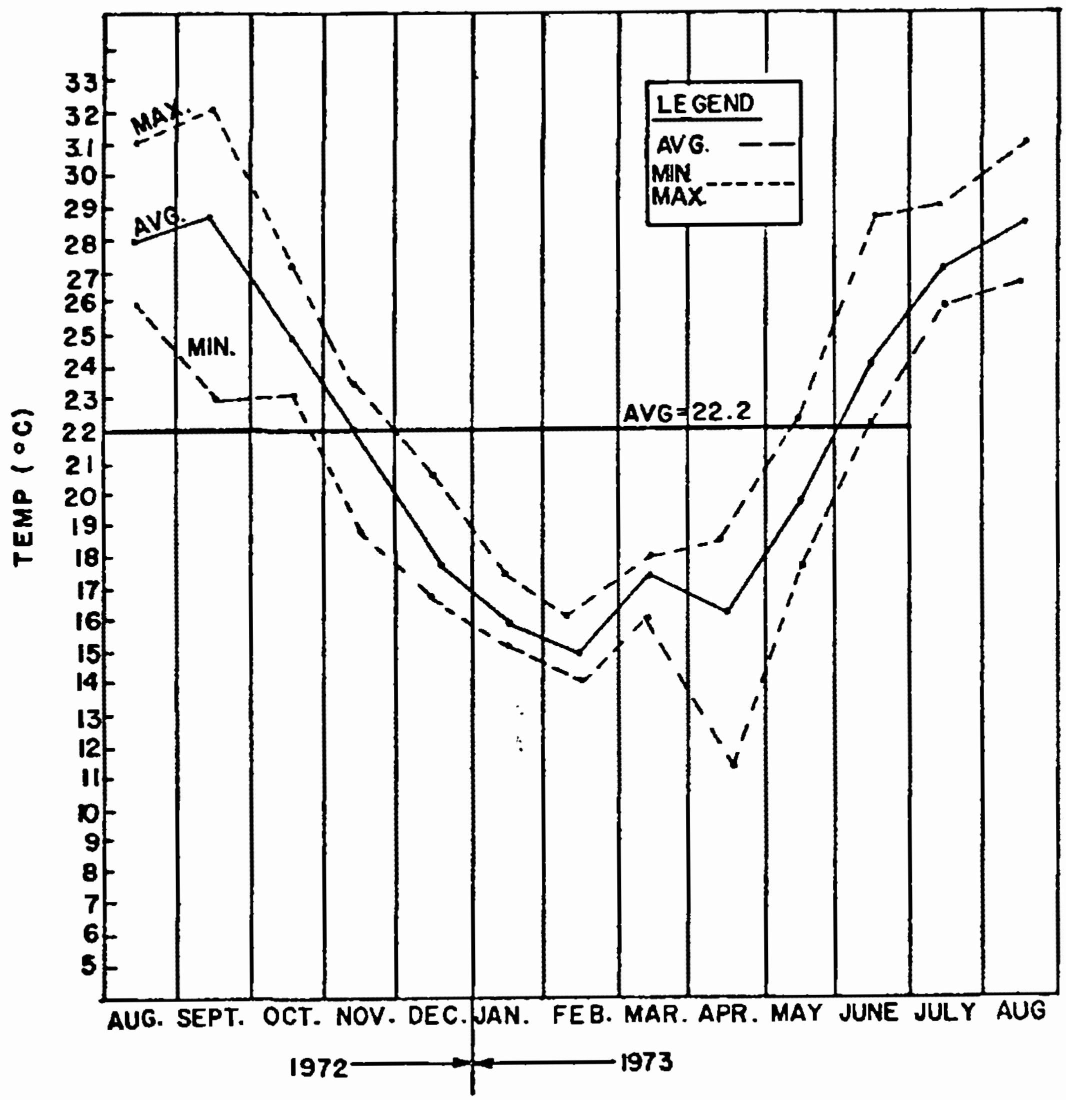


Fig. 7. Monthly variation of biomass temperature in diffused air digester

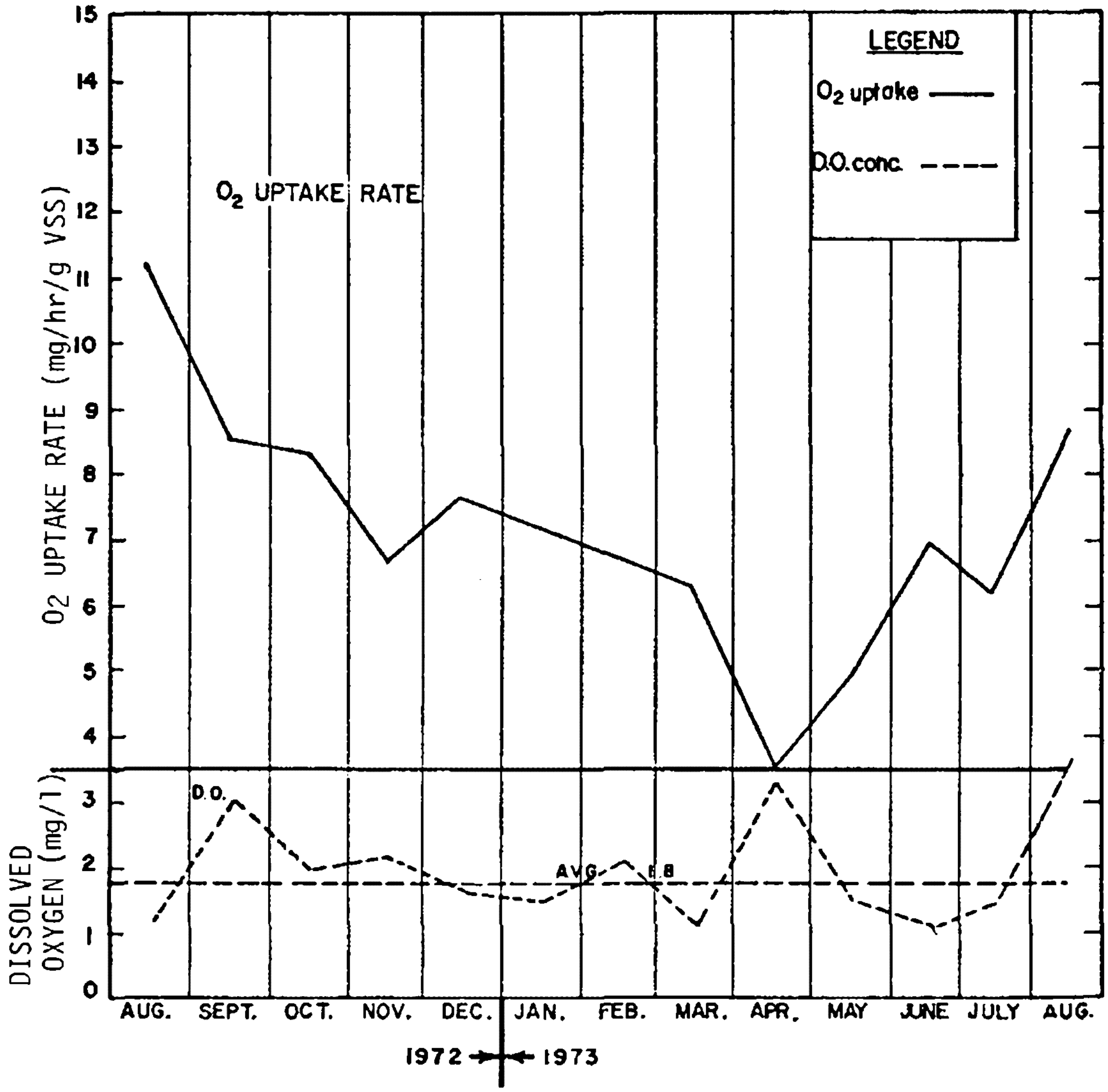


Fig. 8. Monthly variation of biomass oxygen uptake rate and DO in diffused air digester

Table 1. Diffused air digester field data - monthly averages

MONTH	FLOW MGD (1) INF.	FLOW MGD (1) EFF.	TEMP °C	OXYGEN CONC mg/l	OXYGEN UPTAKE RATE R_T	OXYGEN UPTAKE RATE K_T	OXYGEN USED T/DAY	AIR SUPPLY $ft^3/day \times 10^6$ (2)	AIR SUPPLY TONS O_2/DAY	O_2 EFFICIENCY %TRANSFER O_2 USED / O_2 SUPPLIED	O_2 EFFICIENCY DIGESTION O_2 USED / VSS RED	AIR SUPPLY LIQUID VOLUME $cfm/10^3 ft^3/day$ (3)	SLUDGE SETTLEABILITY ml /30 min	SLUDGE SETTLEABILITY ZSV in/hr
AUG. 1972	.371	.336	28.0	1.2	56.0	11.1	7.8	9.9	77.4	10.0	2.1	34.0	"SPLIT"	NA
SEPT.	.339	.336	28.7	3.0	42.0	8.6	6.4	10.0	78.0	8.2	1.6	34.2	527	22
OCT.	.228	.232	25.1	1.9	36.7	8.2	5.5	9.6	74.8	7.4	2.2	33.3	416	38
NOV.	.178	.178	22.0	2.1	33.5	6.6	5.1	5.1	39.7	12.8	2.3	17.6	572	31
DEC.	.508	.507	18.4	1.6	53.2	7.4	9.2	6.2	48.2	19.3	3.2	18.7	789	23
JAN. 1973	.633	.633	16.4	1.4	51.2	7.1	8.3	6.5	50.4	16.7	3.7	21.0	865	15
FEB.	.706	.692	15.8	2.0	38.1	6.5	5.7	7.9	61.6	9.3	1.4	27.4	889	17
MARCH	.507	.505	17.1	1.1	38.8	6.1	5.8	8.8	68.8	8.5	2.2	30.9	895	11
APRIL	.074	.072	15.9	3.2	21.2	3.4	2.9	7.1	55.2	5.2	2.9	24.7	730	11
MAY	.233	.230	20.2	1.4	28.9	4.8	4.4	8.8	65.5	7.3	1.2	29.3	433	28
JUNE	.300	.298	24.3	1.0	38.9	6.8	6.0	11.5	89.6	6.7	1.7	38.9	"SPLIT"	"SPLIT"
JULY	.482	.480	27.6	2.3	45.1	6.3	7.4	12.9	100.6	7.6	2.4	42.6	850	9
AUGUST	.644	.640	28.5	3.6	48.0	8.8	8.3	13.4	104.5	8.0	2.6	45.0	742	12
AVG.	.400	.395	22.2	1.9	40.9	7.1	6.4	9.1	70.3	9.8	2.3	30.6	700	20

(1) MGD x 3785 = m^3/day

(2) ft^3/day x 0.0283 = m^3/day

(3) CFM/$10^3 ft^3$ = $m^3/min/10^3 m^3$

developed by Wuhrmann,[2] and correcting for specific VSS concentration to obtain K_{20} a very significant coefficient of correlation -0.924 between percent VSS reduced and K_{20} was obtained for the period September 1972 through June 1973. It appears that a sludge having a K_{20} of less than 6.0 mg/hr/g VSS shows a high level of VSS stabilization. Conversely, if the value for K_{20} is greater than 6, the degree of VSS reduction is relatively small. Thus, by correcting K_r for temperature, standardized to 20°C, this parameter can be used as a measure of the degree of stabilization of the aerobically digested sludge. A useful criteria would be K_{20} of less than 5 to indicate a sludge of good stability.

In order to determine whether the oxygen uptake test run on a sample collected at the end of "B" pass was representative of the uptake rate for the entire aeration basin, a series of samples at the end of "A", "B" and "C" passes were collected once per shift on two separate days. Temperature was measured in all three passes and the standard deviation from the mean temperature throughout the digester was found to be less than 1.0°C. The highest average uptake rate was experienced on the midnight shift. The results for August 23, 1972 indicated that O_2 uptake rates at "A" pass were 17.4% higher than the daily averages, while the uptake rates at "B" pass were 1.4% lower and those at "C" pass were 16% lower than the daily average.

The results for August 26, 1973 showed the uptake rates at "A" pass to be 9.4% higher, those at "B" pass 3% lower and those at "C" pass 5% lower than the daily average.

Table 2. Oxygen uptake rates in three passes of No. 7 aerobic digester (mg/l/hr)

DATE	TIME	A PASS	B PASS	C PASS	DAILY AVERAGE
8/23/72	10:00 A.M.	96	60	36	64
	6:00 P.M.	72	66	72	70
	2:00 A.M.	76	79	66	73
	AVERAGE	81	68	58	69
8/26/72	10:00 A.M.	63	60	51	58
	6:00 P.M.	63	56	51	57
	2:00 A.M.	83	71	80	78
	AVERAGE	70	62	61	64

A sample collected at the end of "B" pass was therefore considered representative of the average daily uptake rate in the aerobic digestion basin as a whole. This assumption was verified on several other occasions.

Figure 9 indicates that when air is used as the oxygen source, the most efficient utilization of oxygen per unit biomass reduced is obtained with a loading of 1.28 k_gVSS/m^3/day (0.08 lb VSS/ft^3/day) with biomass temperatures above 20°C. In order to aerobically digest one ton of VSS, three times as much oxygen was required at the high loading rate of 3.0 k_gVSS/m^3/day (0.187 lb VSS/ft^3/day) as was required at the optimal loading rate. At the low loading rate of 0.417 k_gVSS/m^3/day (0.026 lb VSS/ft^3/day) the high O_2 requirements may be related to nitrification as well as the diminishing amount of readily biodegradable biomass remaining in the system. At very high loading rates, sludge retention time is so short that the solubilization of VSS barely begins before the active biomass is wasted from the system.

Figure 10 shows the relationship between compressed air supply per unit volume under aeration and the oxygen transfer efficiency of the system. Calculation of oxygen transfer efficiency in the diffused air system required converting oxygen respired (K_r) to tons O_2 utilized per day on the basis of total biomass VSS inventory in the digester. This value was then compared to the tons per day oxygen equivalent of the compressed air supplied to the digester. Air utilization ranged between 0.293 and 0.75 l/sec/m^3 (17.6 and 45.0 cfm/1000 ft^3) with an average annual value of 0.51 (30.6). Oxygen transfer efficiency was highest when temperature was lowest, averaging 9.8% for the entire test period and ranging from a minimum of 5.2% in April 1973 to a maximum of 19.3% in December 1972. The diffused air system is a relatively inefficient method for transferring oxygen from the gaseous to the liquid phase. Oxygen transfer efficiency was found to vary inversely with liquid temperature and directly with side wall depth of liquid in the digester. Figure 11 shows the relationship between O_2 transfer and the above variables (ft/°C x 0.305 = m/°C). An expression of this relationship having correlation coefficient of +0.87 is:

$$Y = 0.12 + 0.31X$$

where Y = ft/°C units

X = percent O_2 Transfer Efficiency

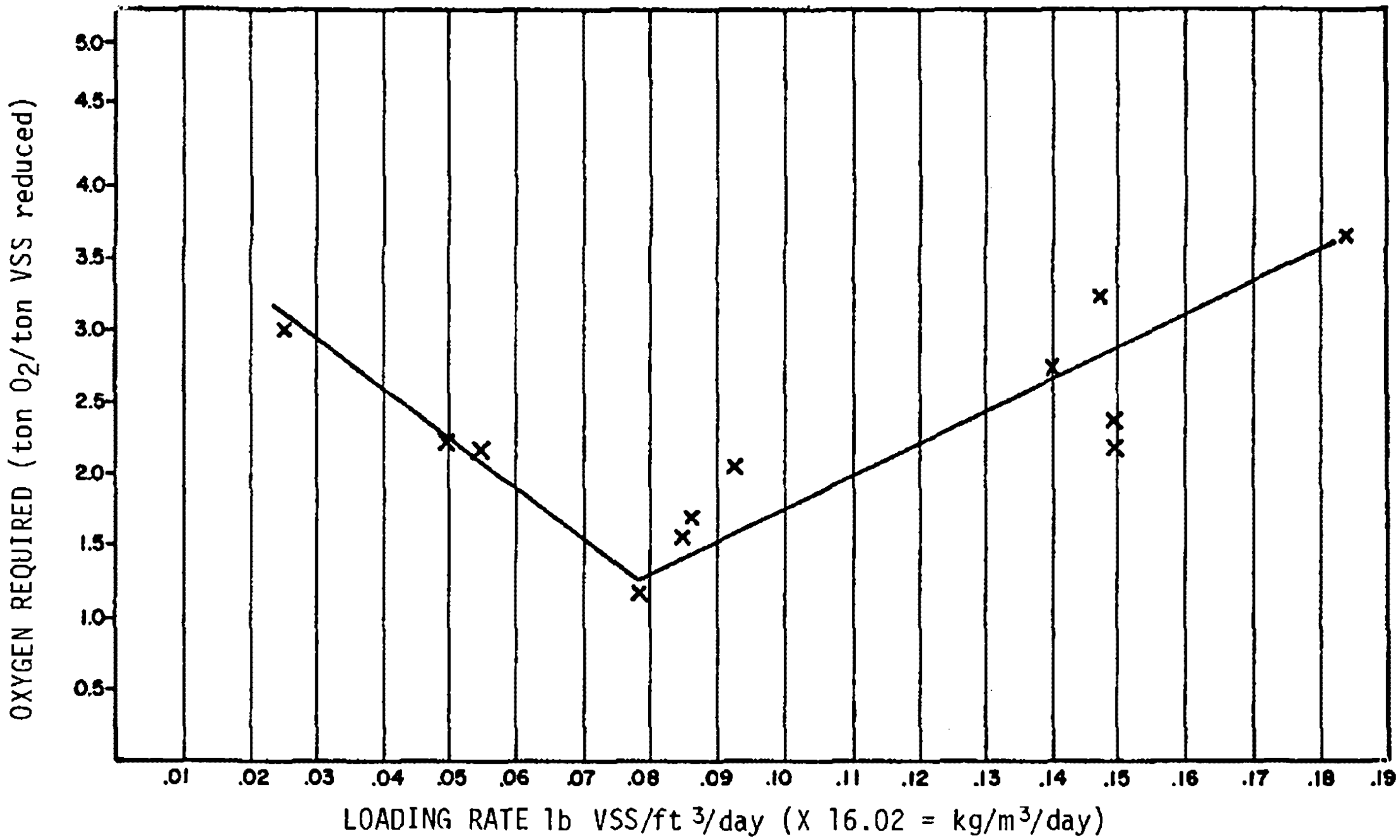


Fig. 9. Effect of sludge loading rate on oxygen requirement of biomass in diffused air digester

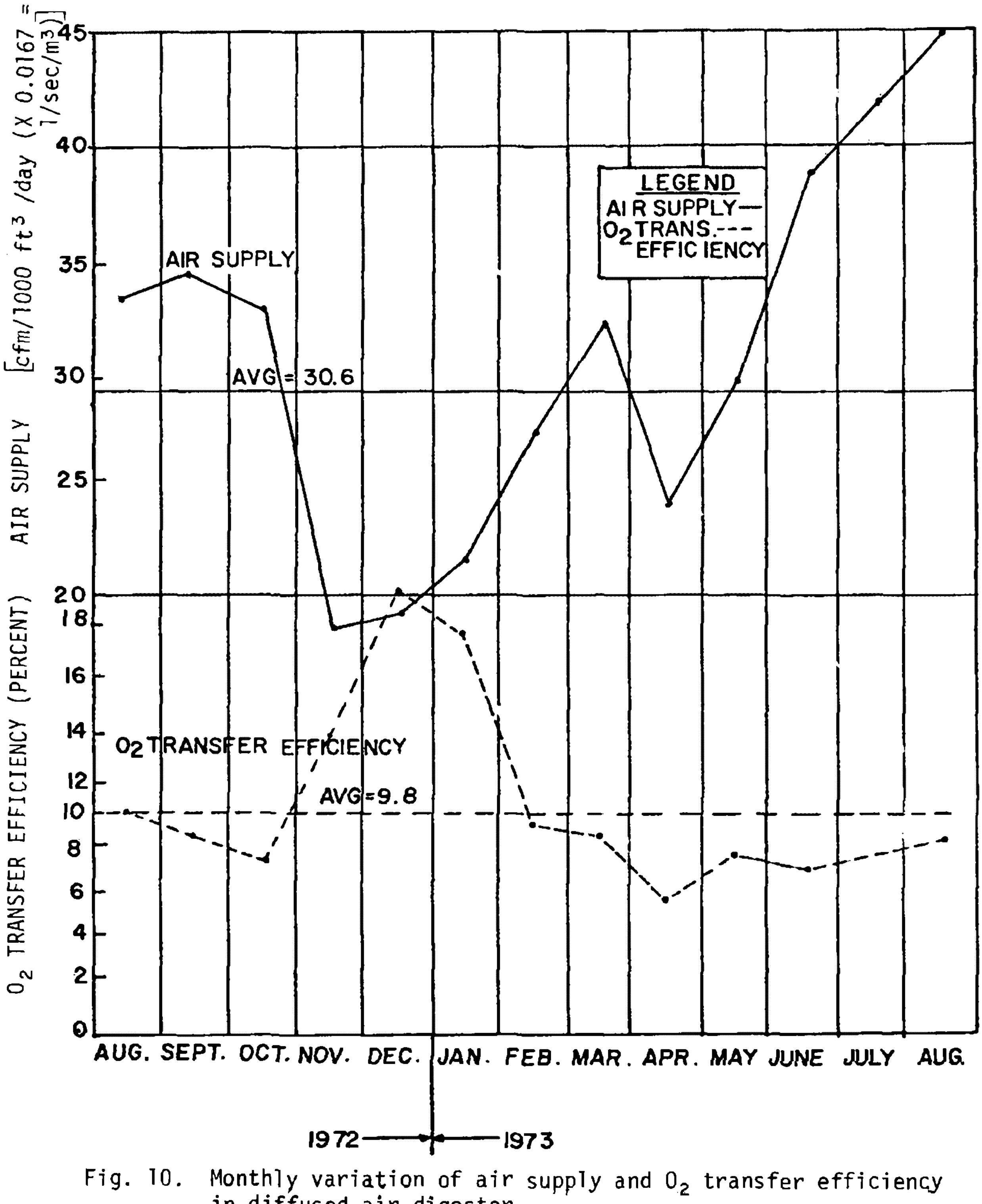


Fig. 10. Monthly variation of air supply and O_2 transfer efficiency in diffused air digester

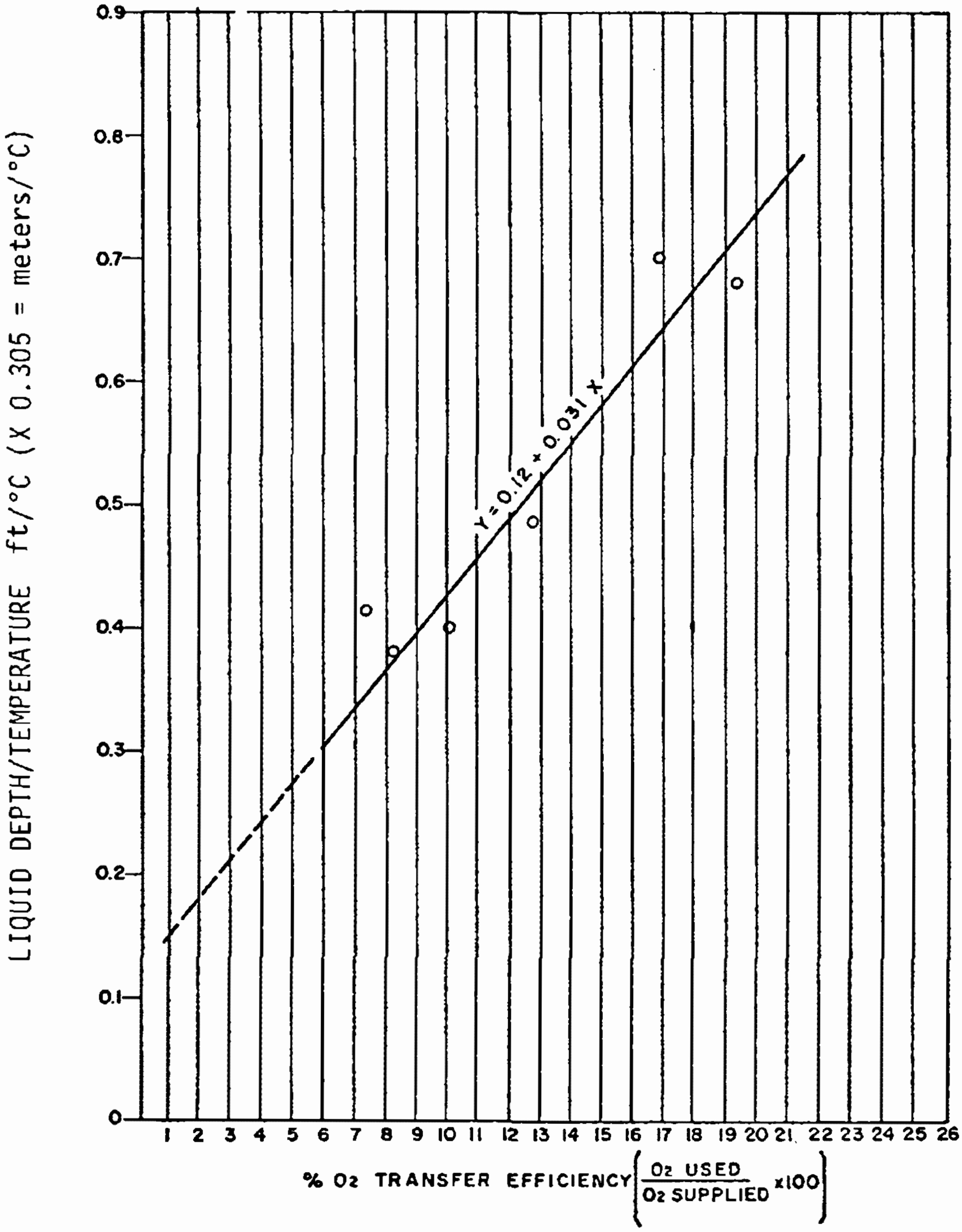


Fig. 11. Oxygen transfer efficiency in diffused air digester as a function of liquid depth/temperature

Figure 12 indicates the settleability of the aerobically stabilized sludge measured both as sludge volume index (SVI) and as zone settling velocity (ZSV). SVI was measured in a 2 litre Mallory jar while ZSV was determined in a 2.45 meter (8.0 ft) deep, 0.153 meter (0.5 ft) diameter column stirred at 10 rph. Excluding those months when the stabilized sludge tended to "split" into a settled and a floated fraction as a result of inadequate DO leading to denitrification, the ZSV averaged 50.8 cm/hr (20 in/hr). For the entire test period, the SVI averaged 114 ml in 30 min/g TSS. A poor correlation (-0.09) was found to exist between ZSV and SVI. At the high solids concentrations maintained in the aerobic digester, SVI calculations are a less sensitive measure of the changing settleability rates than ZSV. When ZSV is multiplied by TSS concentration, a solids weighted settling rate (CiVi) having dimensions $g/cm^2/hr$ is obtained. Figure 13 shows a better correlation (-0.54) between CiVi and SVI than the previously discussed correlation between ZSV and SVI. Figure 14 was obtained by plotting daily solids-weighted settling rates CiVi on temperature versus loading rate coordinates, and then constructing isosettling rate curves. This figure indicates that the best settleabilities were obtained at temperatures of 20-21 $^{\circ}C$, and at a loading rate of 1.28 kg $VSS/m^3/day$ (0.08 lb $VSS/ft^3/day$). A summary of most important field data appears in Figure 15 where average monthly values for SRT, temperature, K_r, O_2 respired/VSS reduced, percent and tons/day VSS reduced are shown in relation to each other. Figures 16 and 17 show monthly variations in VSS and hydraulic loading.

Laboratory Data

Monthly averages of laboratory data for the test period are summarized in Table 3. Table 4 includes the percent change between the influent loading and effluent waste from the digester. Table 5 summarizes aerobic digestion performance data.

Solids Data

TSS and VSS were analyzed by a modification of the Gooch crucible method.[3] Figure 18 shows a schematic interrelationship of the various solids forms undergoing aerobic digestion. The

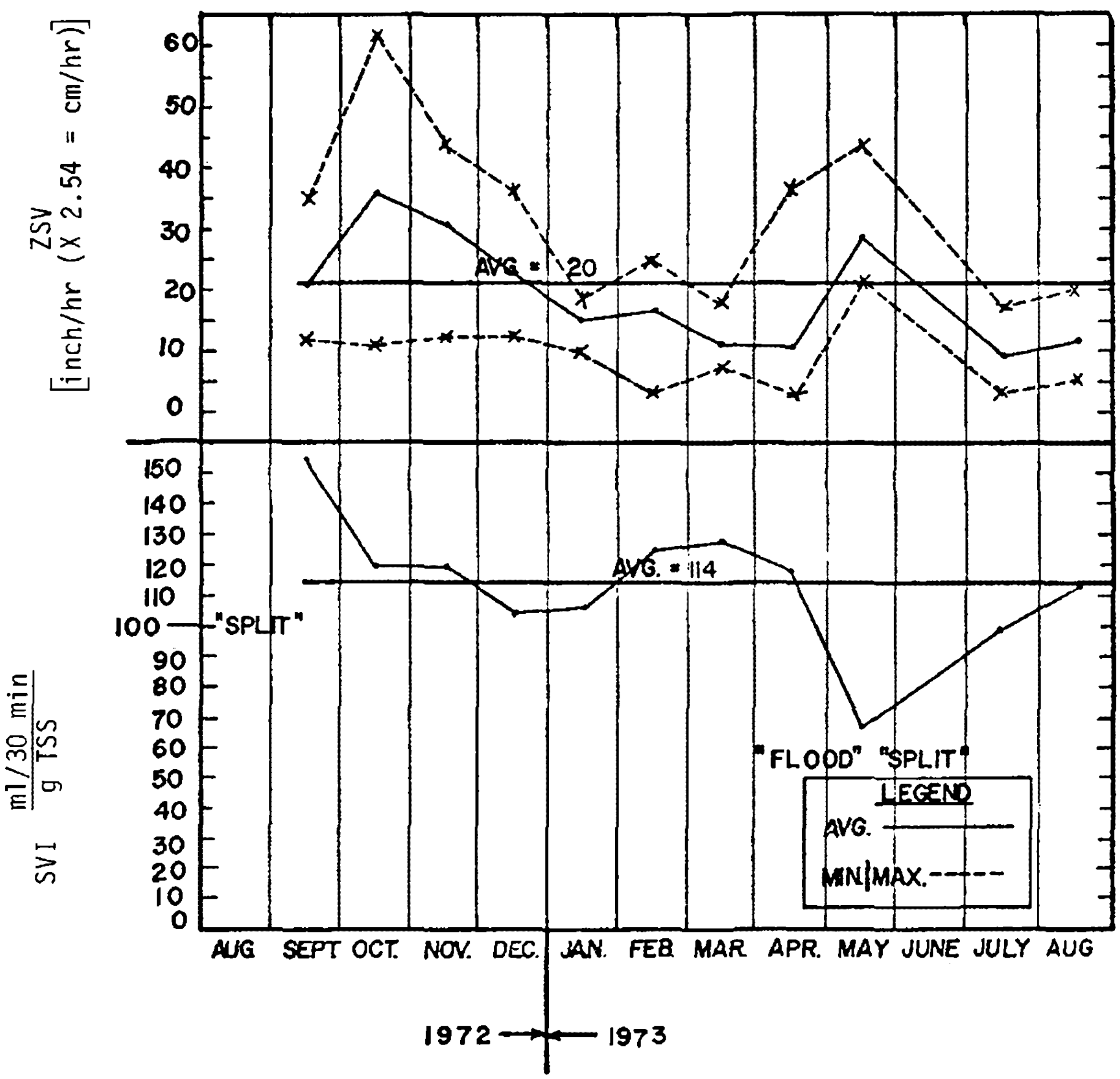


Fig. 12. Monthly ZSV and SVI variation of biomass in diffused air digester

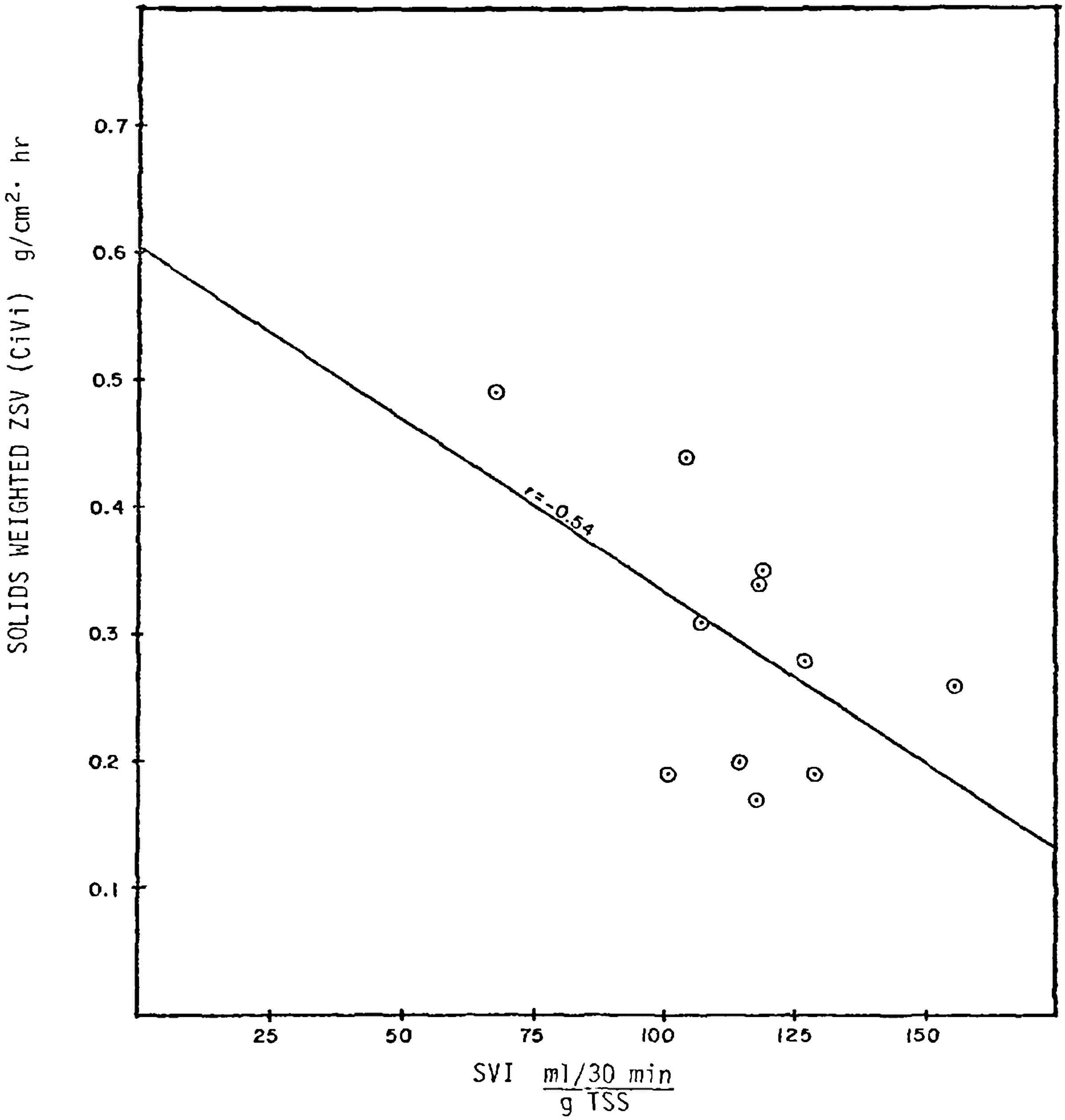
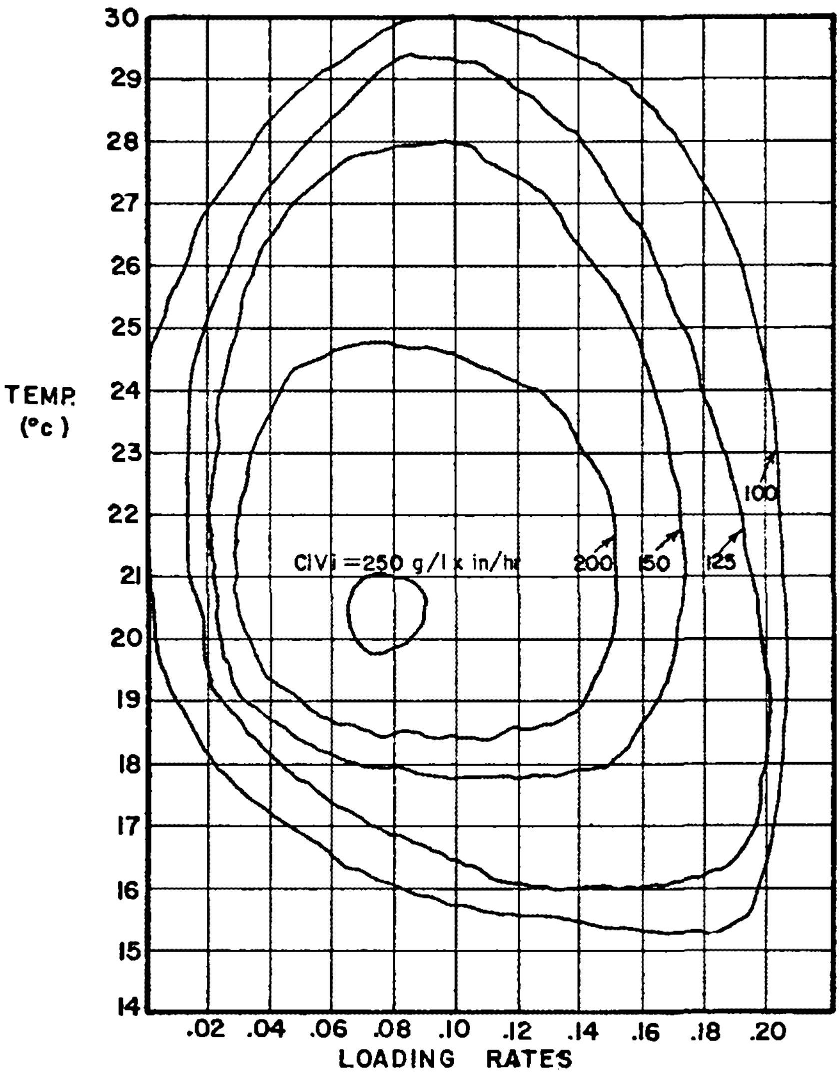


Fig. 13. Correlation of SVI versus solids weighted ZSV in diffused air digester



lb VSS/ft^3/day (X 16.02 = kg/m^3/day)

Fig. 14. Isosettling rates of biomass in diffused air digester as a function of temperature and loading rates

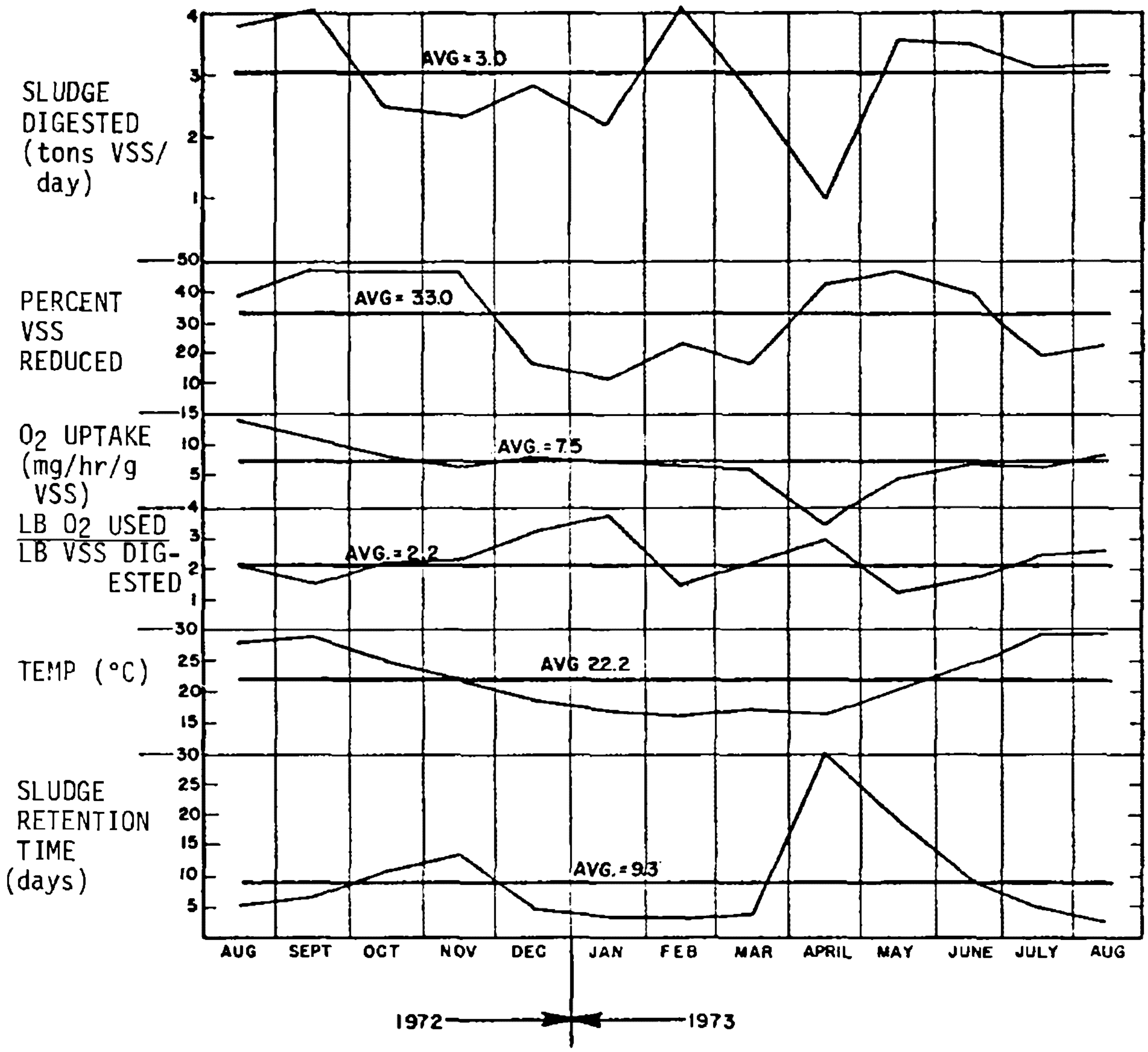


Fig. 15. Monthly variation in diffused air digester average field data

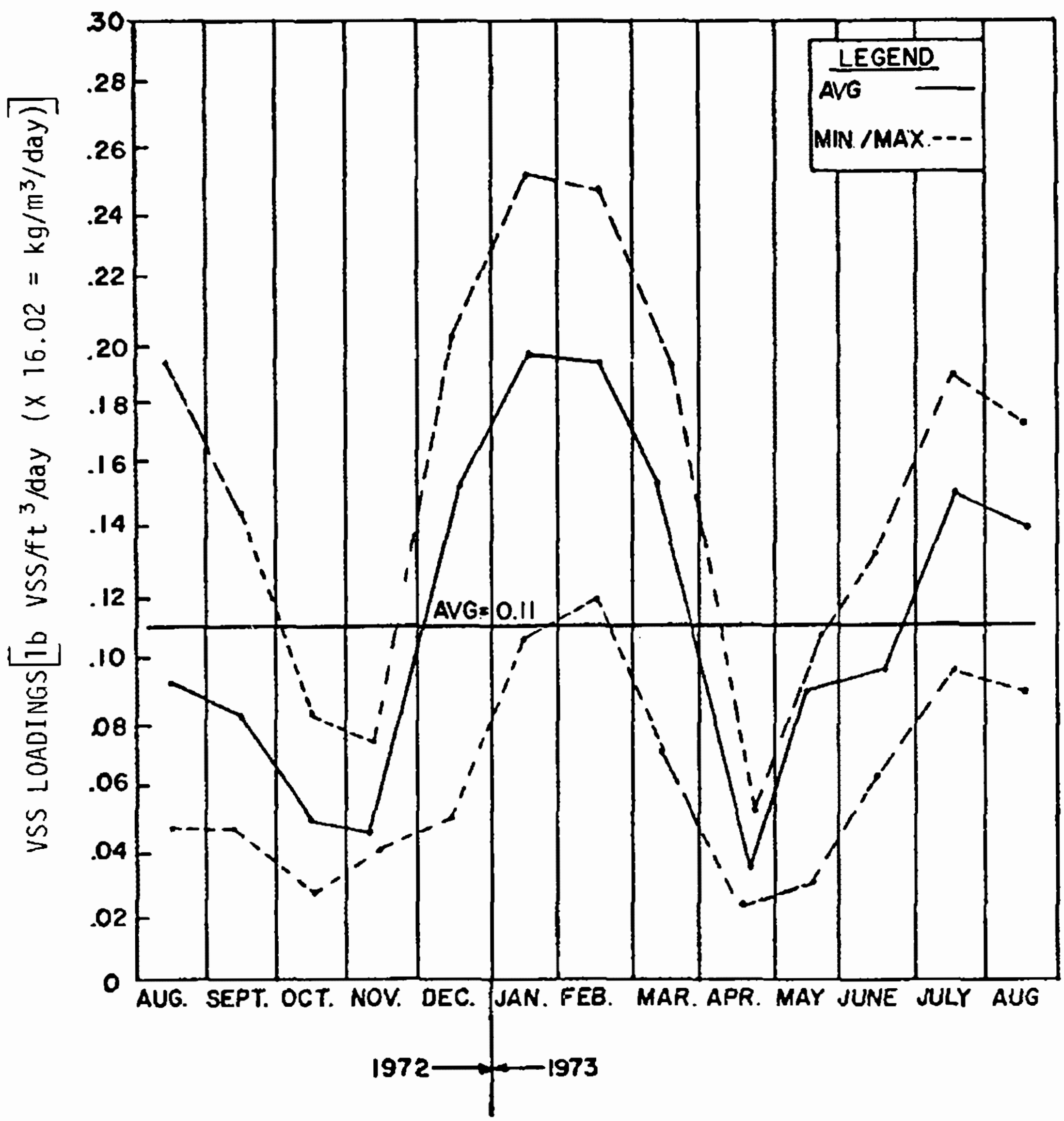


Fig. 16. Monthly variation in volatile solids loadings to diffused air digester

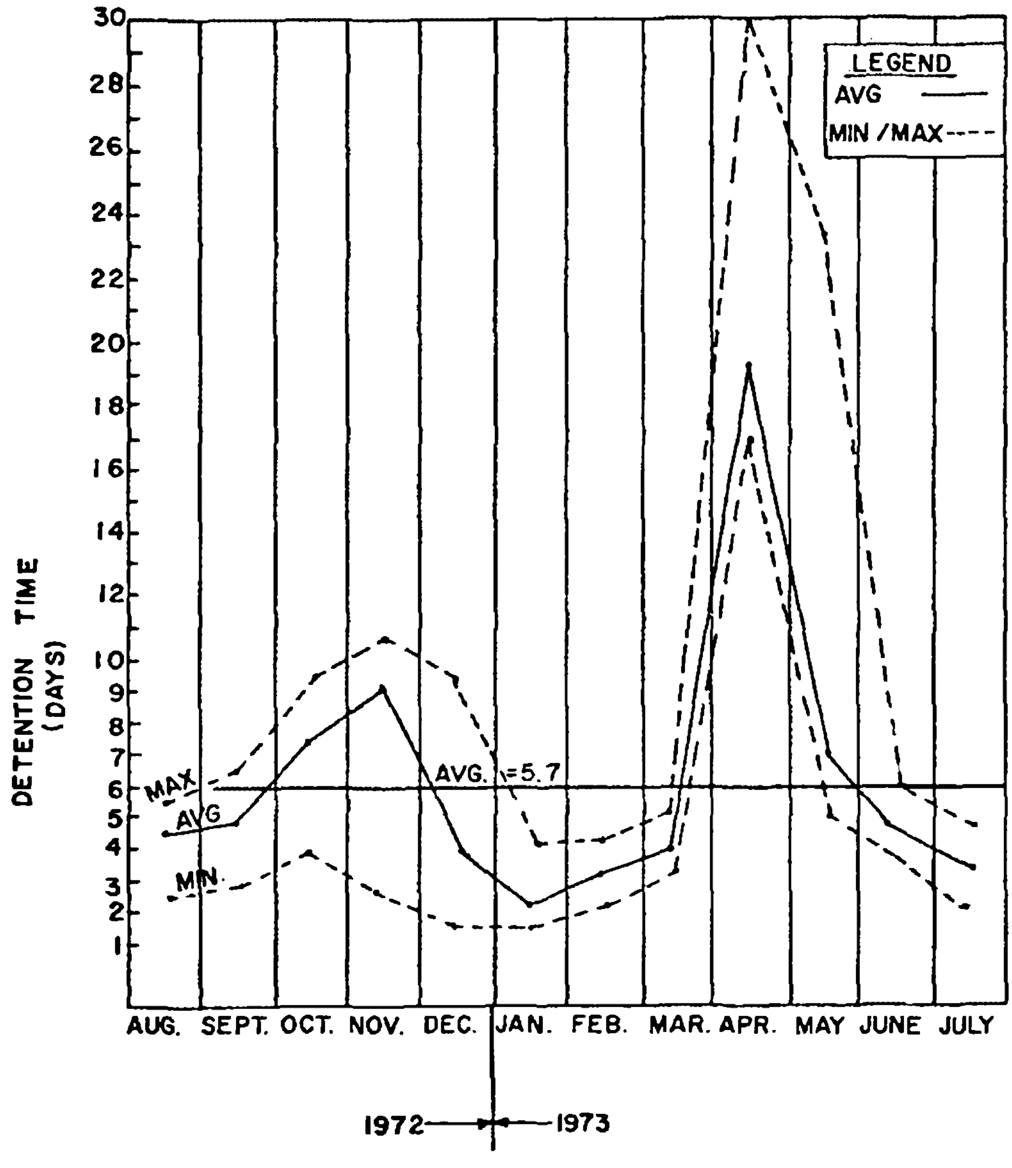
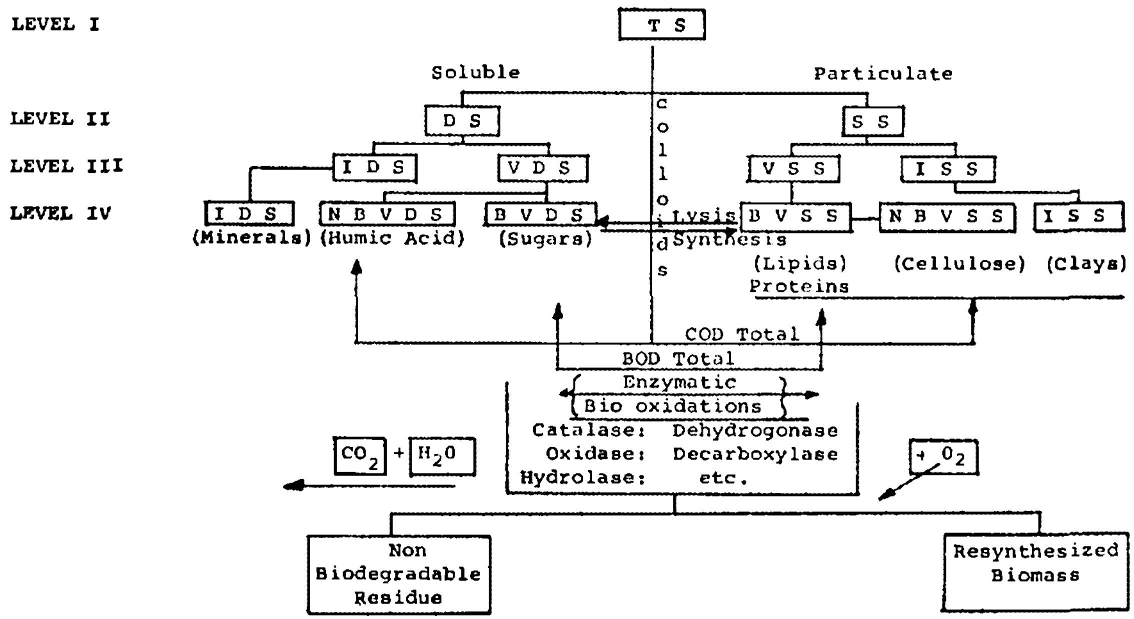


Fig. 17. Monthly variation in diffused air digester hydraulic detention time



LEGEND

T S = Total Solids
D S = Dissolved Solids
S S = Suspended Solids

I D S = Inert D S
V D S = Volatile D S
V S S = Volatile S S
I S S = Inert S S

N B VD S = Non Biodegradable V D S
B V D S = Biodegradable V D S
B V S S = Biodegradable V S S
N B V S S = Non Biodegradable V S S

Fig. 18. Schematic inter-relationships of solid forms undergoing aerobic digestion

Table 3. Diffused air digester laboratory data - monthly average (mg/l unless other units indicated)

MONTH	SAMPLE	TOTAL SOLIDS			SUSPENDED SOLIDS			DISSOLVED SOLIDS			C O D	NITROGEN-N			PO_4-P	COND. µmho/cm^2	pH (units)	ALK. as $CaCO_3$	FECAL COLI. 10^6/ml
		TS	VS	FS	TSS	VSS	FSS	TDS	VDS	FDS		NO_3	NH_4	TKN					
AUG.	INF	8,472	6,491	1,981	7,582	6,275	1,307	890	216	674	10,100	.34	36	617	218	1,407	6.8	479	NA
1972	EFF	6,198	4,177	2,021	5,054	3,839	1,215	1,144	338	806	5,942	27.5	55	438	228	1,626	7.0	424	NA
SEPT.	INF	8,266	6,354	1,912	7,366	6,160	1,206	900	194	706	10,120	.25	29	600	179	1,263	6.9	409	17.0
	EFF	6,193	4,136	2,057	4,688	3,568	1,120	1,505	568	937	5,790	94.0	70	398	168	1,870	6.6	229	0.5
OCT.	INF	7,921	6,287	1,634	7,146	6,121	1,025	775	166	609	10,796	.06	36	641	158	1,232	7.0	437	17.0
	EFF	5,364	3,644	1,720	3,545	2,793	752	1,819	851	968	5,460	128.4	80	396	141	2,154	6.5	104	0.9
NOV.	INF	8,661	6,833	1,828	7,813	6,626	1,187	848	207	641	12,601	.05	35	615	171	1,188	7.0	490	17.0
	EFF	5,825	4,155	1,670	4,449	3,488	961	1,376	667	709	6,033	93.0	91	446	151	2,045	6.6	237	0.6
DEC.	INF	10,225	8,149	2,076	9,386	7,964	1,422	839	185	654	14,616	.03	41	691	147	1,183	7.0	563	6.1
	EFF	8,640	6,571	2,069	7,607	6,325	1,282	1,033	246	787	10,500	.15	23	628	148	1,303	6.9	344	1.7
JAN.	INF	9,804	7,789	2,015	8,926	7,604	1,322	878	185	693	14,416	.03	39	653	199	1,205	7.0	516	20.0
1973	EFF	9,225	7,130	2,094	8,104	6,891	1,213	1,121	239	881	11,985	.06	19	574	203	1,226	6.9	362	17.3
FEB.	INF	8,755	6,610	2,145	7,775	6,470	1,305	980	140	840	10,292	.02	48	620	242	1,251	6.9	430	NA
	EFF	7,420	5,400	2,020	6,385	5,195	1,190	1,035	205	830	8,313	.03	85	567	196	1,543	7.0	595	NA
MAR.	INF	9,240	7,274	1,966	8,296	7,092	1,204	944	182	762	11,452	.04	60	632	126	1,395	6.8	487	8.1
	EFF	7,811	5,797	2,014	6,785	5,552	1,233	1,026	245	781	8,548	.06	101	626	147	1,723	7.0	601	5.3
APRIL	INF	10,534	7,920	2,614	9,513	7,751	1,762	1,021	169	852	12,370	.05	44	738	259	1,377	7.0	524	NA
	EFF	7,509	5,159	2,348	6,089	4,704	1,385	1,418	455	963	7,269	67.8	78	480	213	2,011	6.8	333	NA
MAY	INF	13,189	8,200	4,989	12,047	8,022	4,025	1,142	178	964	12,525	.04	33	784	271	1,555	6.9	563	11.0
	EFF	9,107	5,048	4,059	6,847	4,116	2,731	2,260	932	1,328	6,892	178.0	73	433	282	2,680	6.5	225	1.9
JUNE	INF	10,199	7,404	2,795	9,202	7,198	2,004	997	206	791	11,597	.03	38	664	232	1,182	6.7	520	17.0
	EFF	7,698	4,705	2,993	6,300	4,275	2,025	1,398	430	968	6,700	68.9	55	443	270	1,706	6.7	450	0.7
JULY	INF	11,275	8,415	2,860	10,311	8,186	2,125	964	224	735	12,352	.06	28	776	223	1,196	6.9	582	50.5
	EFF	9,395	6,509	2,886	8,237	6,178	2,059	1,158	331	827	8,969	7.9	73	612	251	1,475	7.0	520	7.3
AUG.	INF	8,517	6,193	2,324	7,575	6,009	1,566	942	209	758	9,277	.02	28	602	205	1,130	7.0	485	24.8
	EFF	7,514	5,269	2,245	6,450	4,905	1,545	1,064	364	700	7,326	3.5	38	505	197	1,302	7.0	453	4.0
AVG.	INF	9,620	7,225	2,395	8,688	7,037	1,651	932	169	745	11,731	.08	38	664	202	1,274	6.9	499	14.2
	EFF	7,531	5,208	2,323	6,195	4,756	1,439	1,335	452	883	7,671	51.5	65	504	200	1,743	6.8	375	3.6

Table 4. Diffused air digester laboratory data - percent change influent versus effluent

Month	TOTAL SOLIDS			SUSPENDED SOLIDS			DISSOLVED SOLIDS			C O D	NITROGEN-N			PO_4-P	CONDUCTIVITY	pH	ALK. as	FECAL COLI
	TS	VS	FS	TSS	VSS	FSS	TDS	VDS	FDS		NO_3	NH_4	TKN		µmho/cm^2	(Units)	$CaCO_3$	x 10^6/ml
AUGUST 1972	-26.8	-35.6	+ 2.0	-33.3	-38.8	- 7.0	+28.5	+56.5	+19.6	-41.2	+ 8.0 x 10^3	+52.8	-29.0	+ 4.6	+15.6	+0.2	-11.5	N.A.
SEPTEMBER	-25.1	-34.9	+ 7.6	-36.4	-42.1	- 7.1	+67.2	+192.8	+32.7	-42.8	+37.5 x 10^3	+141.4	-33.7	- 6.2	+48.1	-0.3	-44.0	-97.1
OCTOBER	-32.3	-42.0	+ 5.3	-50.4	-54.4	-26.6	+ 134.7	+412.7	+59.0	-49.4	+214.0 x 10^3	+122.2	-38.2	-10.8	+74.8	-0.5	-76.2	-94.7
NOVEMBER	-32.7	-39.2	- 8.6	-43.1	-47.4	-19.0	+62.3	+222.2	+10.6	-52.1	+186.0 x 10^3	+160.0	-27.5	-11.7	+72.1	-0.4	-51.6	-96.2
DECEMBER	-15.5	-19.4	- 0.3	-19.0	-20.6	- 9.9	+23.1	+33.0	+20.3	-28.2	+ 0.4 x 10^3	-43.9	- 9.1	+ 0.7	+10.1	-0.1	-38.9	-72.1
JANUARY 1973	- 5.9	- 8.5	+ 3.9	- 9.2	- 9.4	- 8.3	+27.7	+29.2	+27.1	-16.9	+ 0.1 x 10^3	-51.3	-12.1	+ 2.0	+ 1.7	-0.1	-29.8	-13.5
FEBRUARY	-15.2	-18.3	- 5.8	-17.9	-19.7	- 8.8	+ 5.6	+46.4	- 1.2	-19.2	+ .05 x 10^3	+77.1	- 8.5	-19.0	+23.3	+0.1	+38.4	N.A.
MARCH	-15.5	-20.3	+ 2.4	-18.2	-21.7	+ 2.4	+ 8.7	+34.6	+ 2.5	-25.4	+ .05 x 10^3	+68.3	- 1.0	+16.7	+23.5	+0.2	+23.4	-93.5
APRIL	-28.7	-34.9	-10.2	-36.0	-39.3	-21.4	+38.9	+169.2	+13.0	-41.2	+135 x 10^3	+77.3	-35.0	-27.8	+46.0	-0.2	-36.5	N.A.
MAY (flood)	-31.0	-38.4	-18.6	-43.2	-48.7	-32.1	+97.9	+423.6	+37.8	-45.0	+445 x 10^3	+121.2	-44.8	+ 4.1	+72.3	-0.4	-60.0	-82.7
JUNE	-24.5	-36.5	+ 7.1	-31.5	-40.6	+ 1.0	+40.2	+108.7	+22.4	-42.2	+230 x 10^3	+44.7	-33.3	+16.4	+44.3	± 0	-13.5	-96.2
JULY	-16.7	-22.7	+ 0.9	-20.1	-24.5	- 3.1	+20.1	+ 44.5	+12.5	-27.4	+0.13 x 10^3	+160.7	-21.1	+12.6	+23.3	± 0.1	-10.0	-85.5
AUGUST	-11.8	-14.9	- 3.4	-14.9	-18.3	- 1.3	+13.0	+ 74.2	- 7.7	-21.0	+0.17 x 10^3	+35.7	-16.1	- 3.9	+15.2	± 0	- 6.6	-96.1
AVG.	-21.7	-27.9	- 3.0	-28.7	-32.4	-12.8	+43.2	+139.0	+18.5	-34.6	+0.64 x 10^3	+71.1	-24.1	- 1.0	+36.8	- 0.1	-24.8	-83.9

Table 5. Diffused air digester performance calculations

MONTH	S.V.I. ml/30 min/g	SUPERNATANT TURBIDITY JTU	LOADING RATES: VOLUMETRIC (1) lb VSS/ft^3/day	LOADING RATES: ORGANIC VSS INF./VSS INV.	DETENTION TIME: HYDRAULIC (DAYS)	DETENTION TIME: SRT (DAYS)	SOLIDS LOADING TONS/DAY (2): TSS	SOLIDS LOADING TONS/DAY (2): VSS	SOLIDS WASTED TONS/DAY (2): TSS	SOLIDS WASTED TONS/DAY (2): VSS	AEROBIC DIGESTION % VSS RED	AEROBIC DIGESTION VSS T/DAY(2)
AUG. 1972	NA	NA	0.092	.38	4.3	5.6	11.4	9.6	7.3	5.5	39.8	3.8
SEPT.	154	NA	0.085	.29	4.5	6.9	10.6	8.8	6.4	4.9	47.0	4.1
OCT.	119	NA	0.054	.20	7.0	10.9	6.3	5.4	3.4	2.7	47.2	2.5
NOV.	120	NA	0.049	.16	8.6	13.4	5.8	4.9	3.3	2.6	46.2	2.3
DEC.	104	73	0.147	.33	3.7	4.3	20.1	17.0	16.3	13.6	16.7	2.8
JAN. 1973	107	76	0.187	.42	2.6	3.1	23.5	20.0	21.5	18.2	11.2	2.2
FEB.	126	55	0.187	.52	2.2	2.7	22.6	18.8	18.3	14.9	22.4	4.2
MARCH	128	73	0.150	.38	3.1	3.7	17.3	14.8	14.5	11.9	18.1	2.7
APRIL	118	149	0.026	.07	19.8	29.8	3.0	2.4	2.0	1.7	41.5	1.0
MAY	68	161	0.078	.20	7.0	18.2	11.7	7.8	5.9	4.0	45.8	3.6
JUNE	"SPLIT"	179	0.086	.24	5.2	8.6	11.3	8.8	7.1	5.5	39.6	3.5
JULY	101	131	0.150	.33	3.5	4.3	20.6	16.4	16.7	12.5	19.8	3.1
AUGUST	114	109	0.140	.41	2.8	3.3	20.0	15.8	17.3	13.0	20.2	3.2
AVG.	114	112	0.110	.30	5.7	8.8	14.2	11.6	10.8	8.5	32.0	3.0

(1) lb VSS/ft^3/day x 16.02 = kg/m^3/day

(2) Tons/day x 0.907 = tons (metric)/day

total solids (TS) are subdivided into particulate and soluble solids (suspended solids - SS and dissolved solids - DS). The soluble solids are further subdivided into volatile dissolved solids (VDS) and inert dissolved solids (IDS). The particulate suspended solids are also subdivided into volatile suspended solids (VSS) and inert suspended solids (ISS). On a fourth level of differentiation, the VDS are subdivided into biodegradable volatile dissolved solids (BVDS) and non-biodegradable volatile dissolved solids (NBVDS). Similarly, the volatile suspended solids can be divided into biodegradable and non-biodegradable fractions. Considerable confusion exists in the literature with regard to the solids form that is aerobically digested or reduced.[4] Some references base their calculations of mass reduction on total solids,[5] others use total volatile solids,[6] and still others use volatile suspended solids. This study used VSS reduction as the criterion for determining degree of aerobic digestion or stabilization. Collodial materials ranging in size between the suspended and the dissolved fractions were not dealt with separately in this analysis and are assumed to be part of the dissolved solids passing through the average pore diameter of the Gooch filter. Although VSS is the major criterion used for determining the diffused air system performance, biodegradable VSS and COD are also considered when discussing the pure oxygen batch tests. Several lab samples were analyzed separately for suspended, dissolved, and total solids and compared with calculated values. The most reliable results were obtained by directly analyzing suspended and dissolved solids, and adding these values to obtain a calculated total solids value.

Volatile Solids Reduction

Figure 19 shows the volatile solids reduction achieved within the spectrum of temperature and loading conditions encountered during the diffused air study. VSS reductions ranged from 11.2% to 47.2%. Attempts to relate this performance to a single variable were unsuccessful. A complicating factor in correlation analysis was the fact that beyond a certain limiting value for sludge detention time, VSS reduction was asymptotic, approaching but rarely exceeding 50%. When coefficients of correlation were calculated for several environmental-operational functions within the limits previously observed, the most significant correlation +0.93 was observed between VSS reduction, and SRT x temperature (Figure 20). This time-temperature

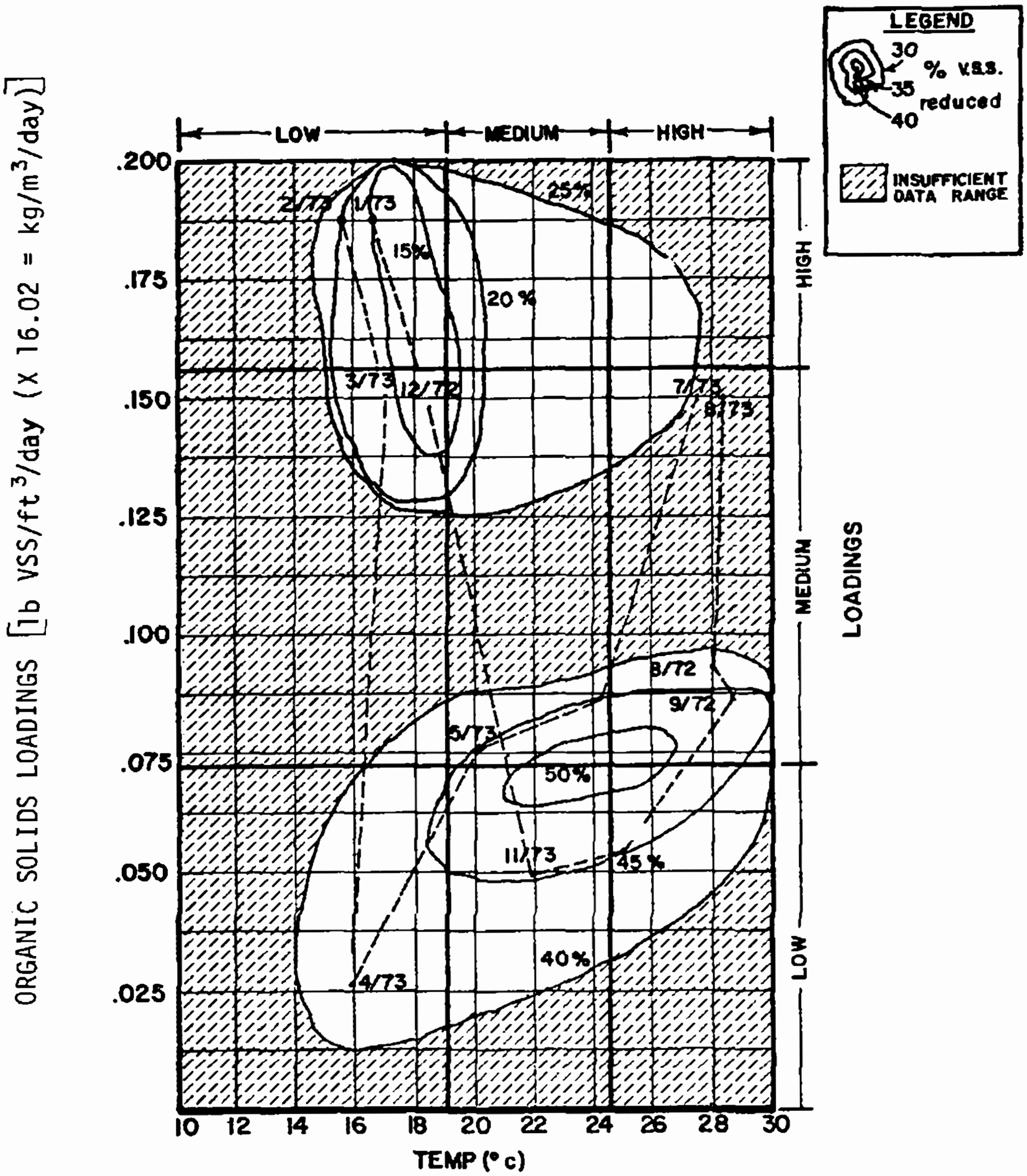
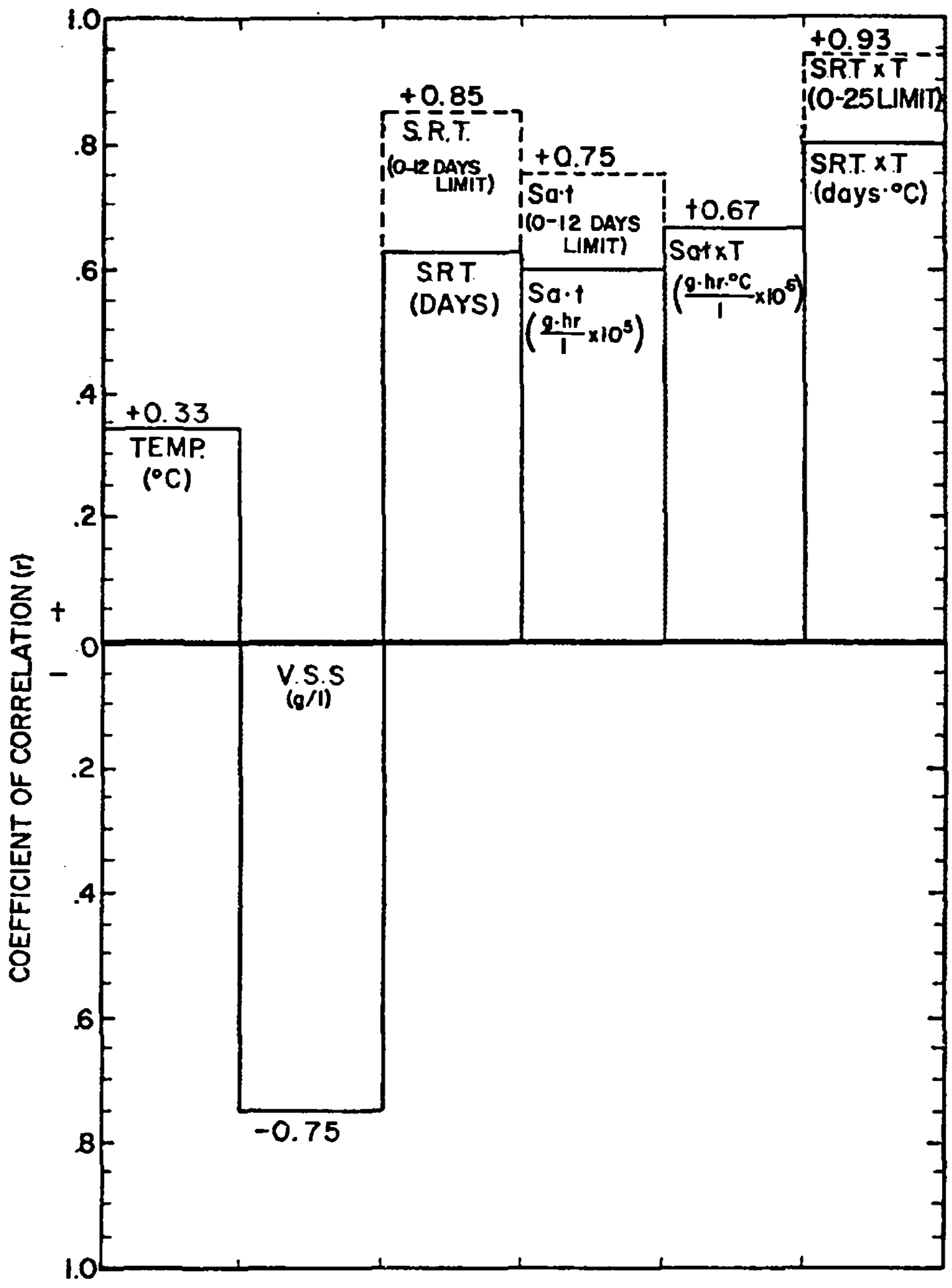


Fig. 19. Spectrum of temperature and loadings versus VSS reductions in diffused air digester



ENVIRONMENTAL OPERATIONAL FACTORS

Fig. 20. Correlation coefficients for various factors influencing VSS reduction in diffused air digester

factor was within the limits of an SRT of 0 - 12 days and a temperature of 12 - 22°C. (Figure 21)

Volatile Solids Residue Change

The VSS/TSS ratio of the WAS influent averaged 81.6% compared with 76.7% in the digested effluent. Thus, a 5% decline in volatile solids residue accounted for an average 32% VSS reduction (Figure 22). If the volatile solids reduction performance were based on a VS/TS ratio as is commonly used when calculating anaerobic digestion performance[7] rather than a VSS/TSS ratio, a 7% decline in volatile solids residue would account for a 30% VS reduction.

A definition of solids reduction under aerobic conditions must, therefore, take into account both solubilization of particulates as well as carbon loss in a gaseous form. Changes in kinetic equilibrium between particulate biomass undergoing enzymatic solubilization and soluble substrate being resynthesized back to particulate biomass, may account in part for these differences in calculated biomass reductions. Suspended solids undergoing aerobic stabilization are converted to dissolved solids, water and gas (mainly carbon dioxide). Figure 23 and 24 indicate that as TSS conversion increases, the rate of solubilization also increases. For example, during October, 1972 when TSS conversion performance was at a maximum, increase in the effluent TDS accounted for approximately 30% of the TSS converted. In March 1973, however, when TSS reduction was minimal, TDS increase accounted for only 5% of the TSS converted. The volatile fraction of Metro WAS must be reduced from an average 80% to less than 60% in order to avoid potentially obnoxious odors, particularly if the stabilized sludge is to be spread on land. This degree of volatile solids reduction has been impossible to achieve at Metro for up to thirty days SRT in this study (excluding the nonrepresentative May 1973 "flood period"). The volatile fraction of the aerobically stabilized sludge can however be further reduced to less than 60% by either chemical oxidation (ozonation) or subsequent anaerobic digestion of the aerobic digester effluent.

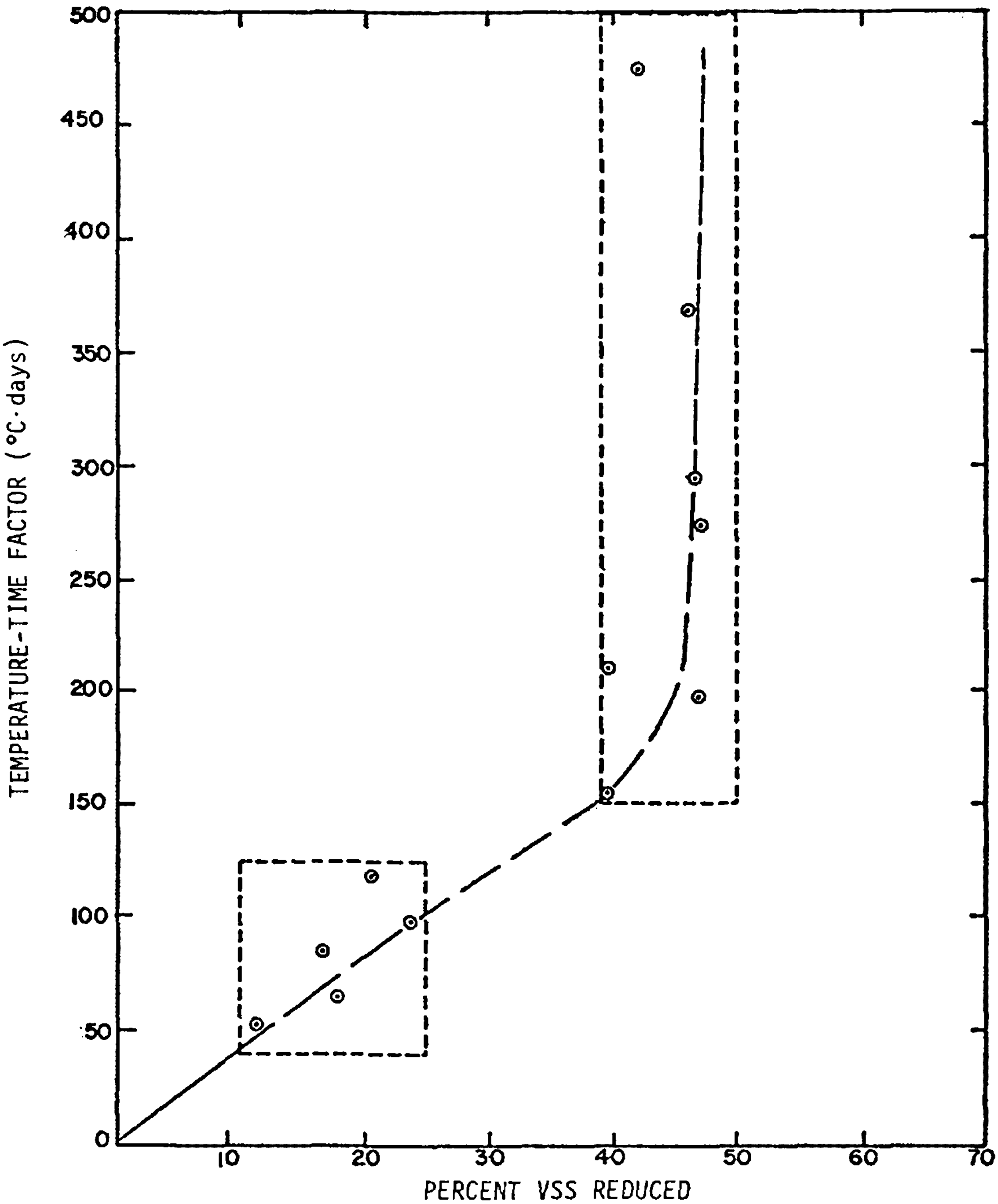


Fig. 21. Temperature-time factor versus percent VSS reduced in diffused air digester

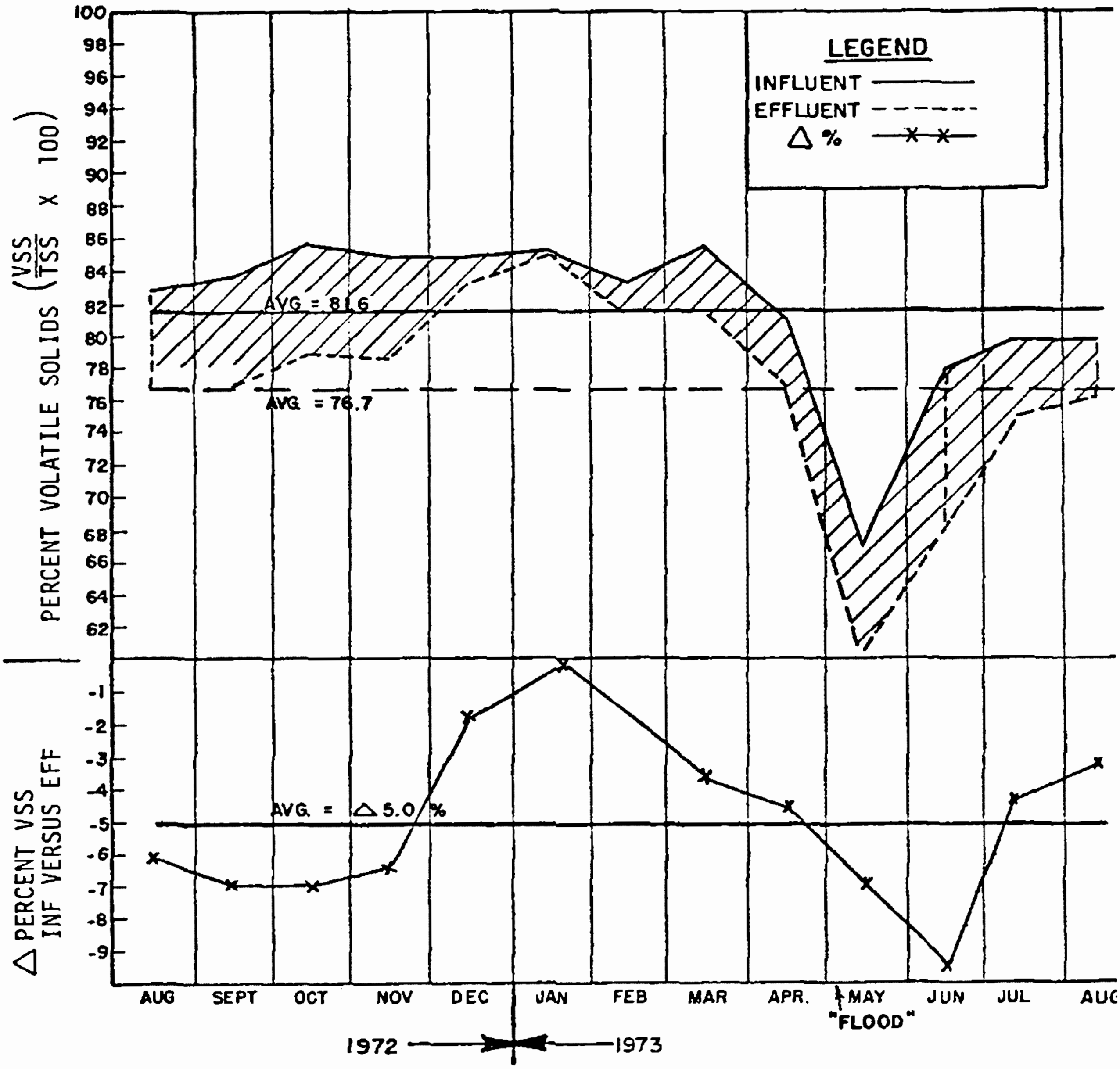


Fig. 22. Monthly variation in percent VSS between influent and effluent of diffused air digester

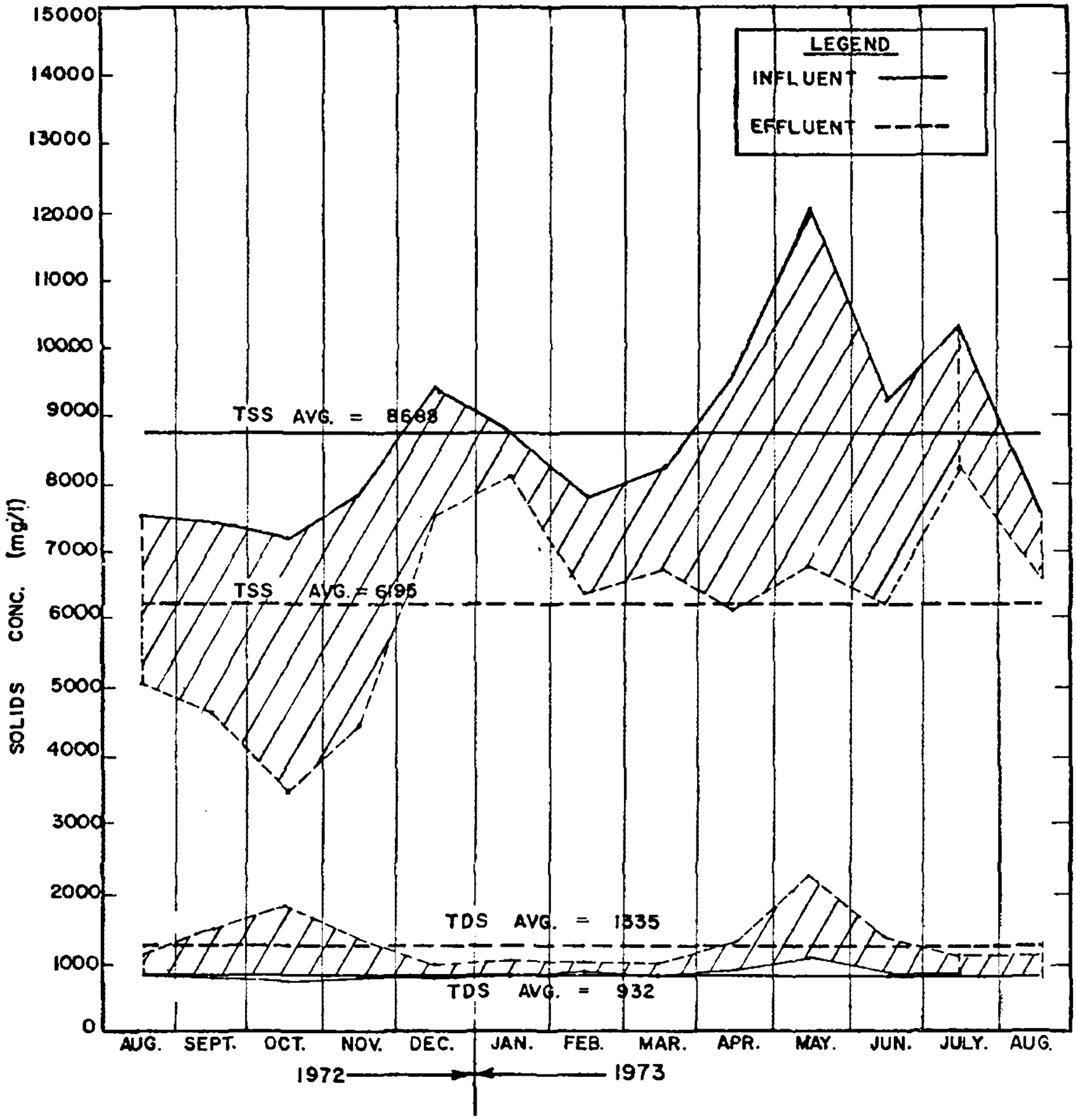


Fig. 23. Monthly variation of influent and effluent TSS and TDS in diffused air digester

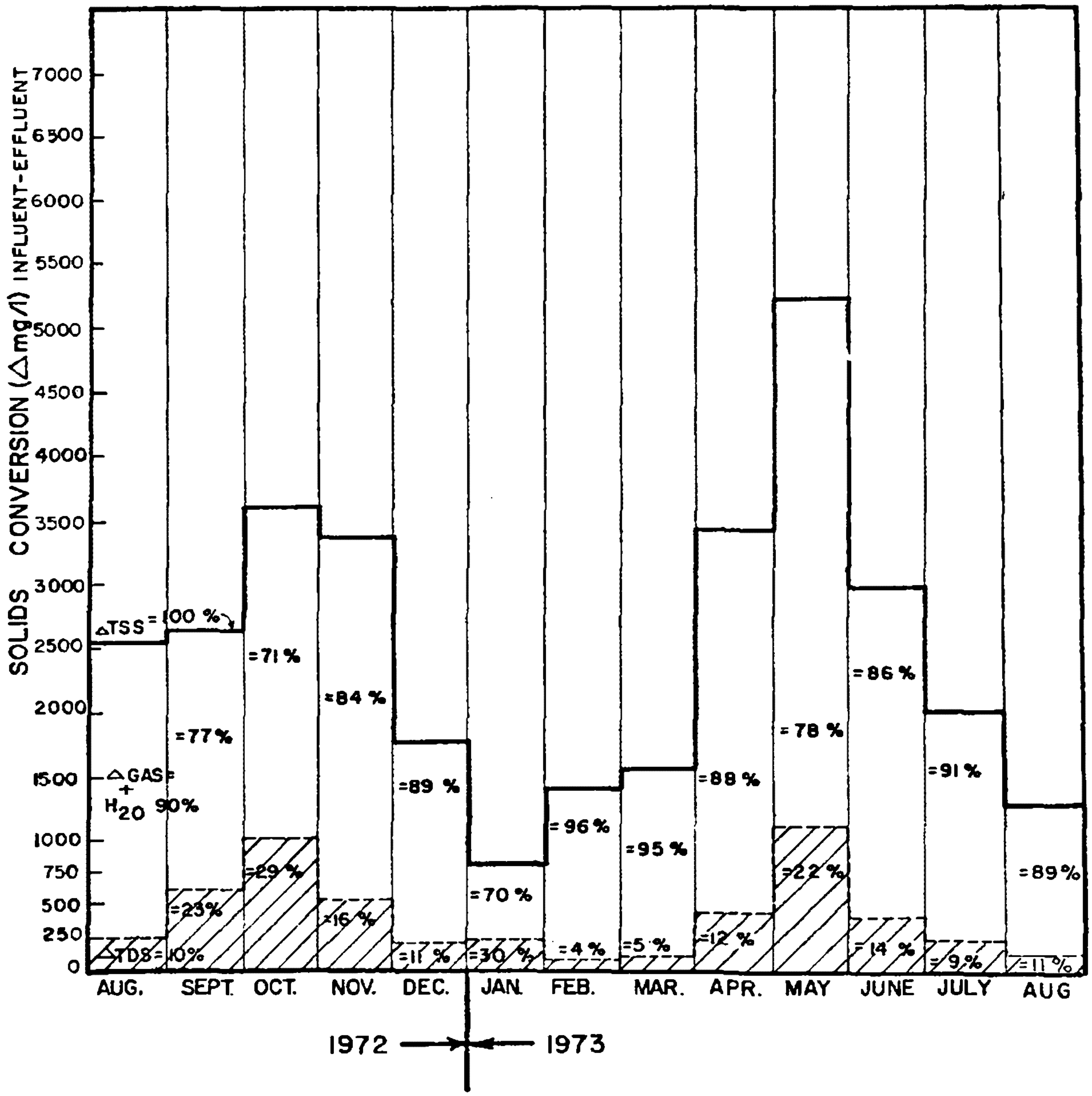


Fig. 24. Monthly variation in solids conversion to dissolved and gaseous end products in diffused air digester

Digester Performance as a Function of SRT

R. C. Loehr in his paper "Aerobic Digestion - Factors Affecting Design"(8) wrote, "Different rates of sludge oxidation and oxygen utilization are due to different starting points ... (but) few authors report the sludge ages of solids entering the aerobic digester. The percent volatile solids reduction of a sludge with a high sludge age will be less than that of a sludge with a low sludge age. For waste sludges with a high sludge age, much of the sludge oxidation has taken place in the activated sludge (secondary) system." In order to test this hypothesis against Metro data, the average monthly SRT of the waste activated sludge in the secondary system prior to loading to the digester was calculated. These data are shown in Table 6.

For an SRT range in the activated sludge system between 4.2 and 25.6 days, very little effect on VSS reduction was observed. For example, during April 1973 when the highest secondary SRT occurred, VSS reductions were 41.5%. When the lowest secondary SRT of 4.2 days occurred in March 1973, VSS reduction was only 18.1%.

For equivalent conditions of total SRT (sludge age in secondary aerator plus aerobic digester), the degree of volatile solids reduction should, according to Loehr, have been almost identical. However, the 10^{o}C drop in temperature between September (28.7^{o}C and SRT 12.8 days) and December (18.4^{o}C and SRT 12.6 days) actually resulted in a three fold drop in digestion efficiency. In September, VSS reduction averaged 47% compared to only 16.6% in December. The results obtained at Metro did not support the contention that SRT in the activated sludge system alone is a major influence on VSS reduction in the aerobic digester. A better correlation (+0.53) was found between total SRT and percent VSS reduced. VSS reduction is apparently most sensitive to environmental conditions during digestion rather than to sludge prehistory.

VSS Materials Balance

Analysis of Metro operational data indicated that a good approximation of the average biomass concentration to be used in calculation of solids inventory was obtained by using the formula:

Table 6. Monthly variation of SRT and VSS reduced in diffused air digester

MONTH	SRT (DAYS)			PERCENT VSS REDUCED	PERCENT VOLATILE SOLIDS		
	Before Digestion	During Digestion	Total		Before Digestion	After Digestion	Δ%
8/72	4.8	5.6	10.4	39.8	82.8	76.0	-6.8
9	5.9	6.9	12.8	47.0	83.6	76.1	-7.5
10	9.2	10.9	20.1	47.2	85.7	78.8	-6.9
11	11.1	13.4	24.5	46.2	84.8	78.4	-6.4
12	8.3	4.3	12.6	16.7	84.8	83.1	-1.7
1/73	6.0	3.1	9.1	11.2	85.2	85.0	-0.2
2	5.0	2.7	7.7	22.4	83.2	81.4	-1.8
3	4.2	3.7	7.9	18.1	85.5	81.8	-3.7
4	25.6	29.8	55.4	41.5	81.5	77.3	-4.2
5 (Flood)	7.6	18.2	25.8	45.8	66.6	60.1	-6.5
6	6.4	8.6	15.0	39.6	78.2	67.9	-10.3
7	5.0	4.3	9.3	19.8	79.4	75.0	-4.4
8	6.2	3.3	9.5	20.2	79.3	76.0	-3.3
AVG.	8.1	8.8	16.9	32.0	81.6	76.7	-4.9

$$\text{Inventory Concentration} = \frac{\text{Influent} + \text{Effluent}}{2}$$

i.e. If influent solids concentration = 8000 mg/l
effluent solids concentration = 4000 mg/l
inventory concentration
(calculated) = 6000 mg/l

Spot checks using a Biospherics suspended solids meter in all three passes of the test basin showed this to be a valid approximation. All inventory calculations were, therefore, based on this formula. The VSS balance in the test digester over the thirteen month period 8/1/72-8/31/73 indicate the following:

Influent loading	=	4600 Tons VSS
Effluent wasting	=	3360 Tons VSS
Initial inventory	=	44 Tons VSS
Final inventory	=	34 Tons VSS

VSS reduction due to aerobic digestion

$$= \text{Inf} - (\text{Eff} \pm \Delta\text{Inv})$$
$$= 4600 - (3360 - 10)$$
$$= 1250/4600$$
$$= 27.2\%$$

Nitrogen Balance

Using the VSS materials balance, a nitrogen balance was calculated. The inventory change in total nitrogen forms (TKN plus NO_3-N) over the test period was negligible (-0.93 tons N). The change between influent and effluent of NH_4-N was +21.2 tons, of NO_3-N was +36.4 tons, and of TKN was -76.7 tons. The difference between the total nitrogen forms loaded to the digester (434.0 tons) and the nitrogen leaving the system in the effluent (393.2 tons) represents an unaccounted for loss of 40.8 tons. This nitrogen loss is attributed to denitrification (9.6% of the total nitrogen loading to the system). It is assumed that denitrification occurred when periods of maximum nitrification coincided with periods of insufficient oxygen due to the shutting off of air in "C" pass for dewatering purposes. This resulted in conversion of NO_3 to N_2 gas. The "split"-float phenomenon during August 1972 and June 1973 tends to substantiate this supposition, as calculated denitrification losses during these months averaged 23% of the total nitrogen load to the system. Because of the denitrification-flotation problem resulting from dissolved oxygen depletion, the decanting operation was discontinued in September 1972.

The effects of cold temperature on aerobic digestion performance were most pronounced during the last two weeks of November 1972. In particular, the inhibition of organic nitrogen mineralization to ammonium and nitrate ions was evident during this period. A decline in calculated denitrification to less than 3% of the total nitrogen loaded to the digester occurred during November 1972. The dramatic impact of sudden cold temperature change is illustrated in Table 7 which compares at a constant loading rate various parameters associated with nitrification, two weeks "before" and two weeks "after" the sudden onset of the first winter snows (November 15, 1972).

Table 7. Effect of "Cold Shock" on Nitrification Parameters

PARAMETER	UNITS	INFLUENT	EFFLUENT "BEFORE"	EFFLUENT "AFTER"
Nitrate - N	mg/l	0.05	174	0.08
Ammonium - N	mg/l	35	145	29
Organic - N	mg/l	580	320	390
Alkalinity as $CaCO_3$	mg/l	490	110	364
pH	Units	7.0	6.0	7.0
Temperature	^oC	-	25.0	19.0

According to Downing[9] the growth constant (μ max) for nitrosomonas is 0.33/day at 20°C and this compares with 0.448/day at 25°C (Figure 25). Downing also determined that the rate of nitrification is independent of ammonium concentrations above 3.0 mg/l NH_4. In the diffused air digester, the WAS influent ammonium concentration averaged 38 mg/l with a minimum concentration of 28 mg/l and thus did not limit the nitrification rate.

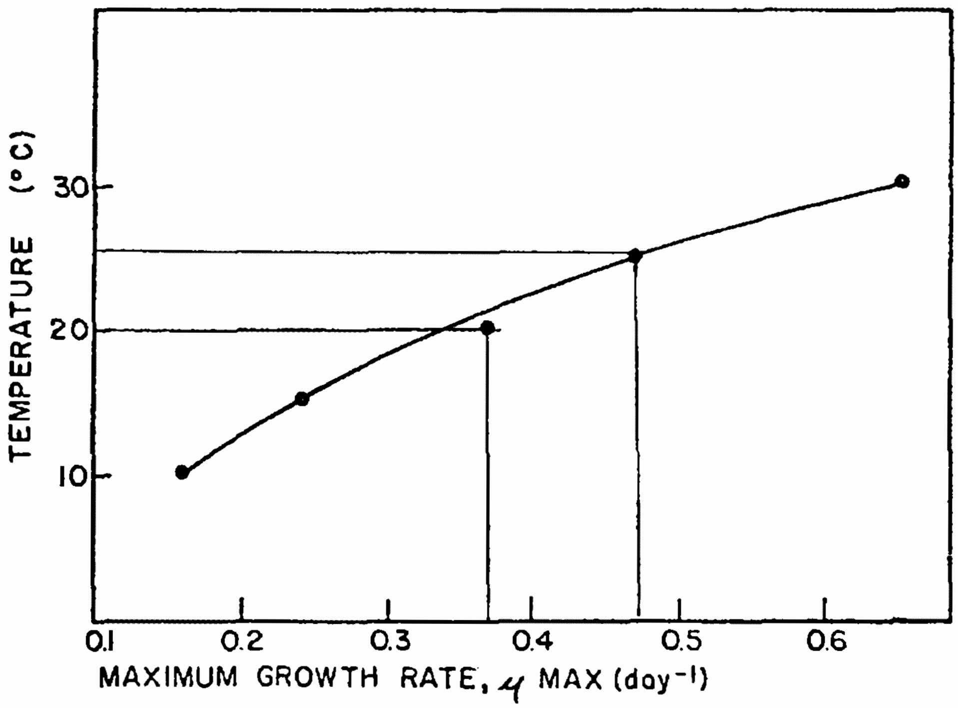


Fig. 25. Temperature effects on growth rate of nitrifying bacteria (after Downing)

The observed decline in nitrification rate with decreasing temperature (-7% per 1°C) should theoretically have required a 14°C drop in the biomass temperature to account for the drop in nitrification during the latter half of November 1972. In order to determine whether other factors beside temperature could account for the cessation of nitrification, the aerobic digestion system was analyzed for heavy metals. No unusually high concentrations of nickel, copper, zinc, etc., were noted. No other signs of toxic effects such as a decline in O_2 uptake rates were observed during this period. It is, therefore, assumed that the cumulative drop in liquid temperature of approximately 1°C per day over a four day period (11/8 - 11/12/72) resulted in a "cold shock" to the sensitive nitrifying bacteria. Nitrification was reestablished in April 1973 even though the average monthly temperature declined in April to a minimum of 15.9°C indicating gradual adaptation of the nitrifying biomass to the colder temperature. During April the high SRT in the digester of 29.8 days was sufficient to maintain high nitrification rates despite the cold temperature. In July 1973, when biomass temperature rose 28.0 °C, and SRT in the digester dropped to 4.3 days, nitrification inhibition was again observed but this time because of the low SRT.

Figure 26 shows that a poor correlation -0.28 existed between dissolved oxygen concentration and nitrification. Both the highest and lowest nitrification rates occurred at DO concentration of 1.4 mg/l. No significant correlation was observed between temperature standardized oxygen uptake rate (K_{20}) and nitrification rates. In fact, the highest degree of nitrification occurred when K_{20} was below 5.9 mg/hr/g VSS. By applying Downing's temperature correction to nitrifying bacteria activity, the important effect of SRT on nitrification rate is apparent. The most significant correlation +0.96 between nitrification rates and environmental conditions was found for the temperature-time factor SRT (days) x temperature (°C) (Figure 27). Nitrate levels in excess of 100 mg/l NO_3-N were observed when the temperature-time factor exceeded 200. Figure 28 and 29 show the influent and effluent monthly variations for nitrate, ammonium and TKN concentrations. Detection limit for NO_3-N was 0.01 mg/l.

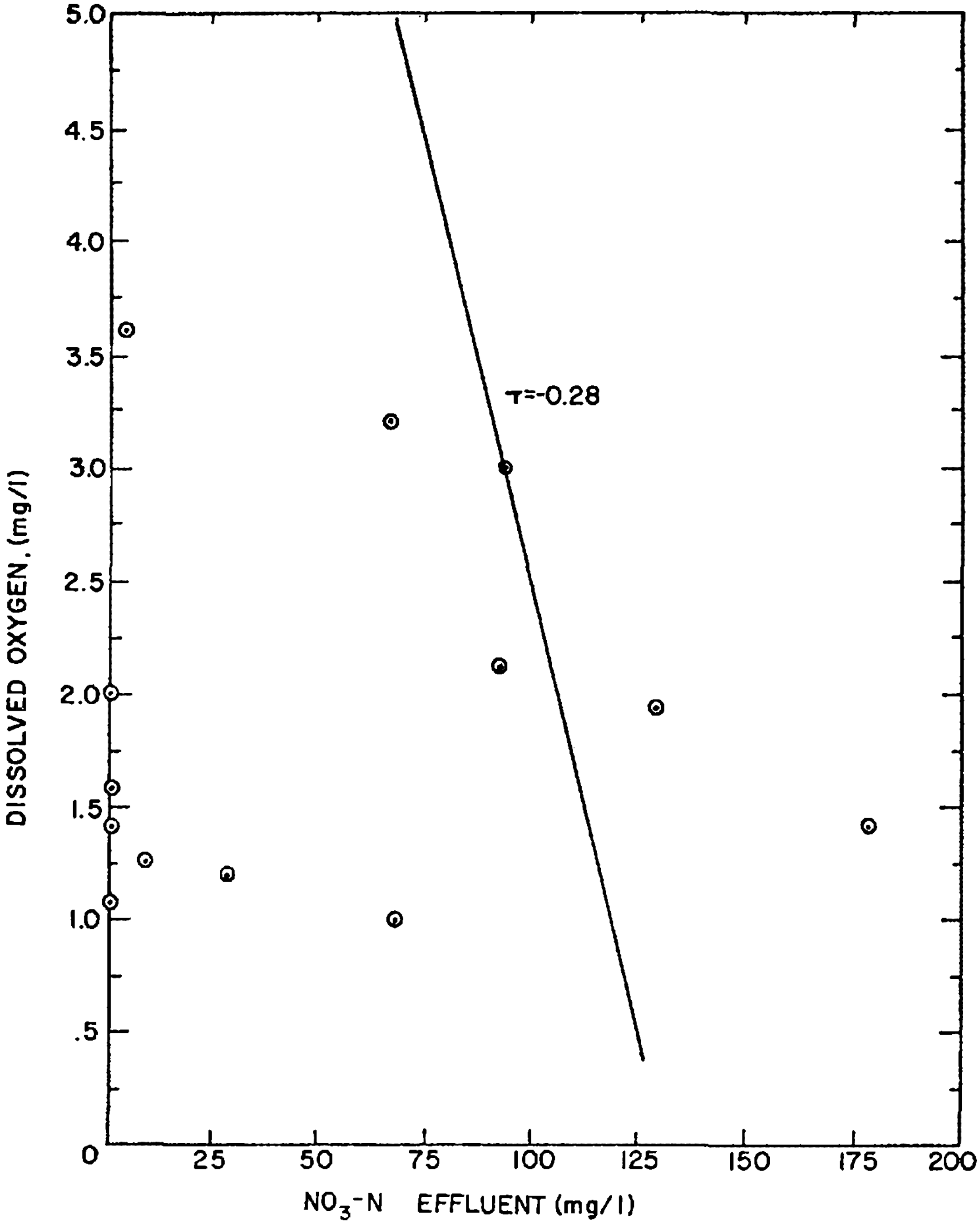


Fig. 26. Influence of DO on nitrification in diffused air digester

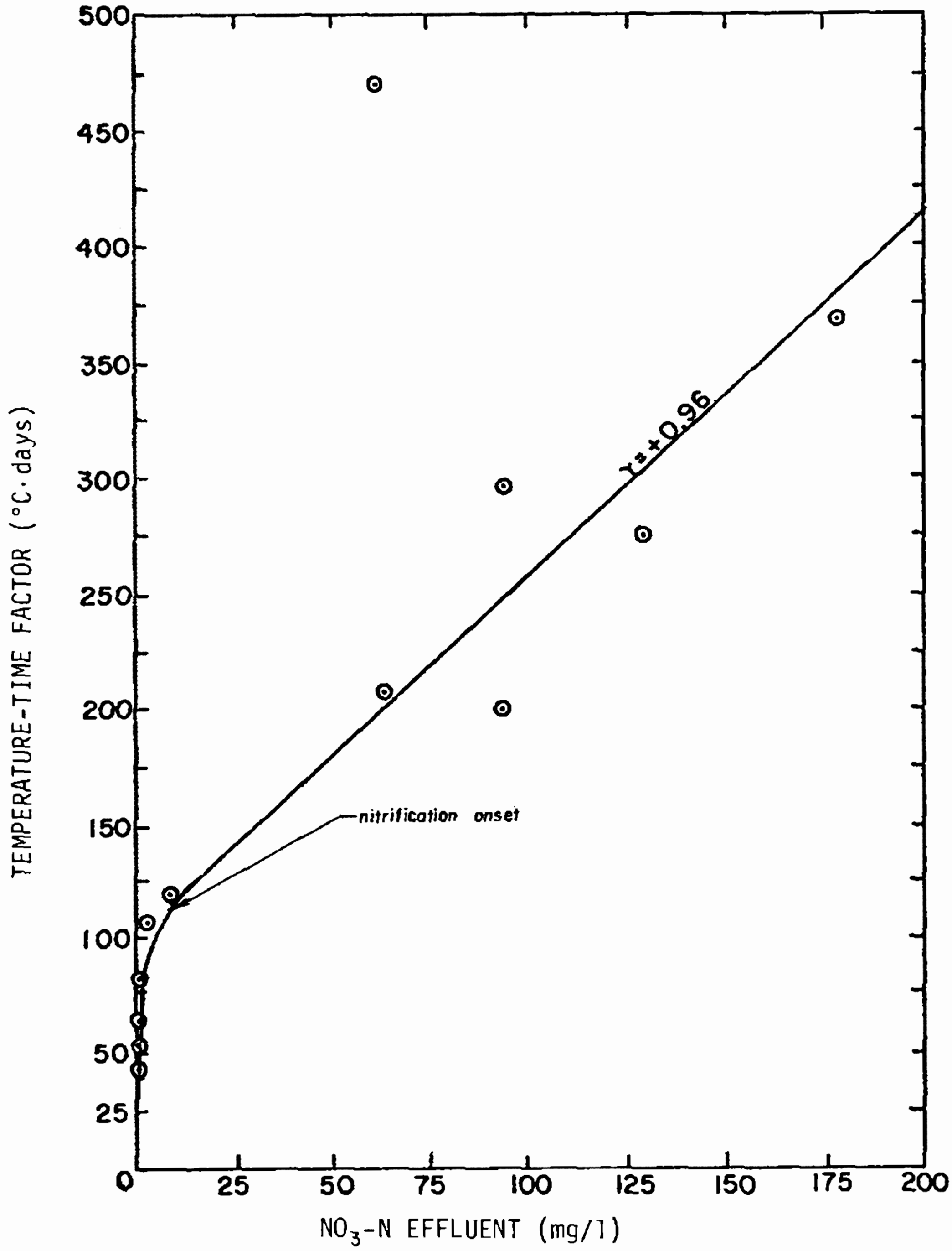


Fig. 27. Effect of temperature-time factor on nitrification in diffused air digester

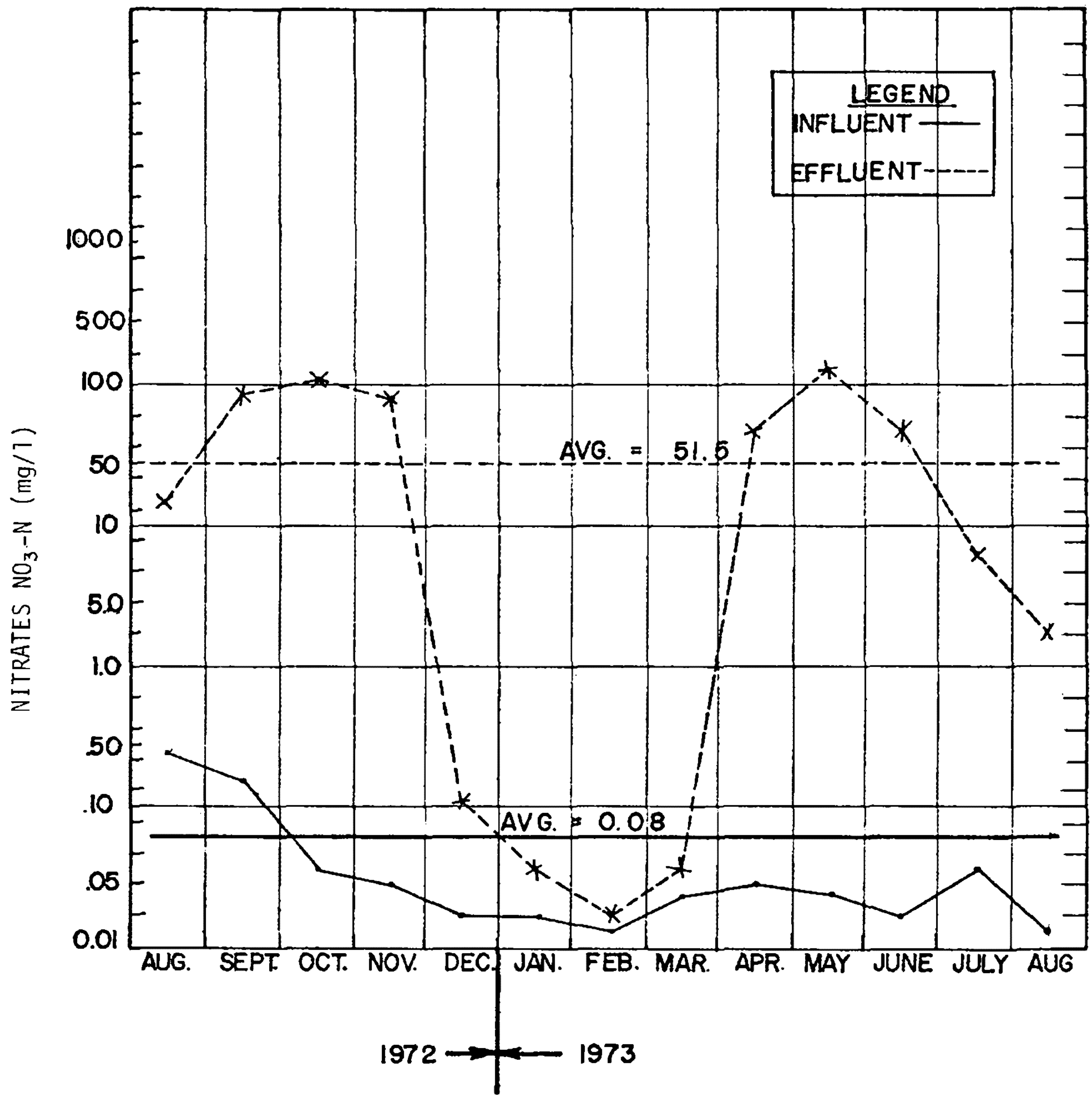


Fig. 28. Monthly variation of nitrates in diffused air digester influent and effluent

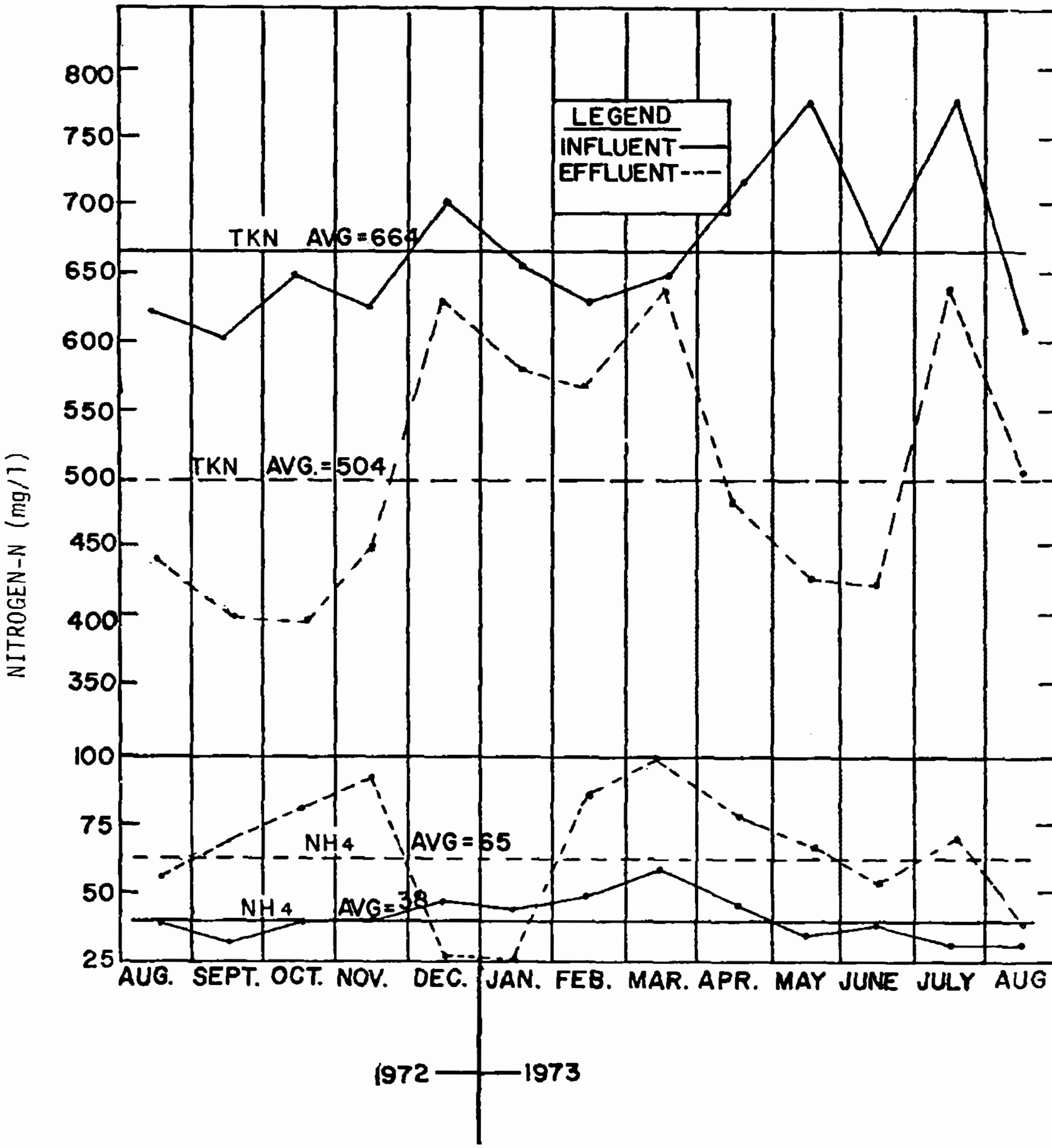


Fig. 29. Monthly variation of TKN and NH_4-N in diffused air digester influent and effluent

Alkalinity and pH

Figure 30 shows the parallel trends between alkalinity and pH changes as they relate to nitrification rates. During the months August - November 1972,the effluent pH was approximately 0.5 units lower than the influent pH, and the alkalinity was approximately 200 mg/l less in the effluent than in the influent. At the end of November 1972 when nitrification ceased, the pH and alkalinity of the influent remained virtually unchanged compared to the effluent. The onset of nitrification in April 1973 coincided with a reduction in the effluent of pH and alkalinity. The best performance, measured as percent VSS reduction (Table 5) occurred when nitrification was highest, and pH and alkalinity differential between the influent and the effluent was maximal. Measurement of pH in the influent and the effluent can indicate the degree of stabilization achieved during periods of nitrification.

Conductivity

Figure 31 shows the change in electrical conductivity between the influent and the effluent. As was the case with pH and alkalinity, the best performance (August - November 1972, and April - June 1972) coincided with the highest differential in conductivity between the influent and the effluent. Figure 32 shows a very high degree of correlation +0.94 between the change in conductivity and the percent VSS reduced. When the conductivity change between influent and effluent was less than 25%, the percent VSS reduced was also less than 25%. Conversely, when the conductivity change was greater than 40%, the percent VSS reduced was also greater than 40%. Electrical conductivity differential measures the degree of mineralization. The correlation between TDS and electrical conductivity was therefore very high. Thus, another simple method for estimating the degree of stabilization achieved is measuring the change in electrical conductivity between the influent and effluent.

COD

The percent COD reduction between influent and effluent (Table 4) correlated very well with the VSS reduction. Figure 33 shows

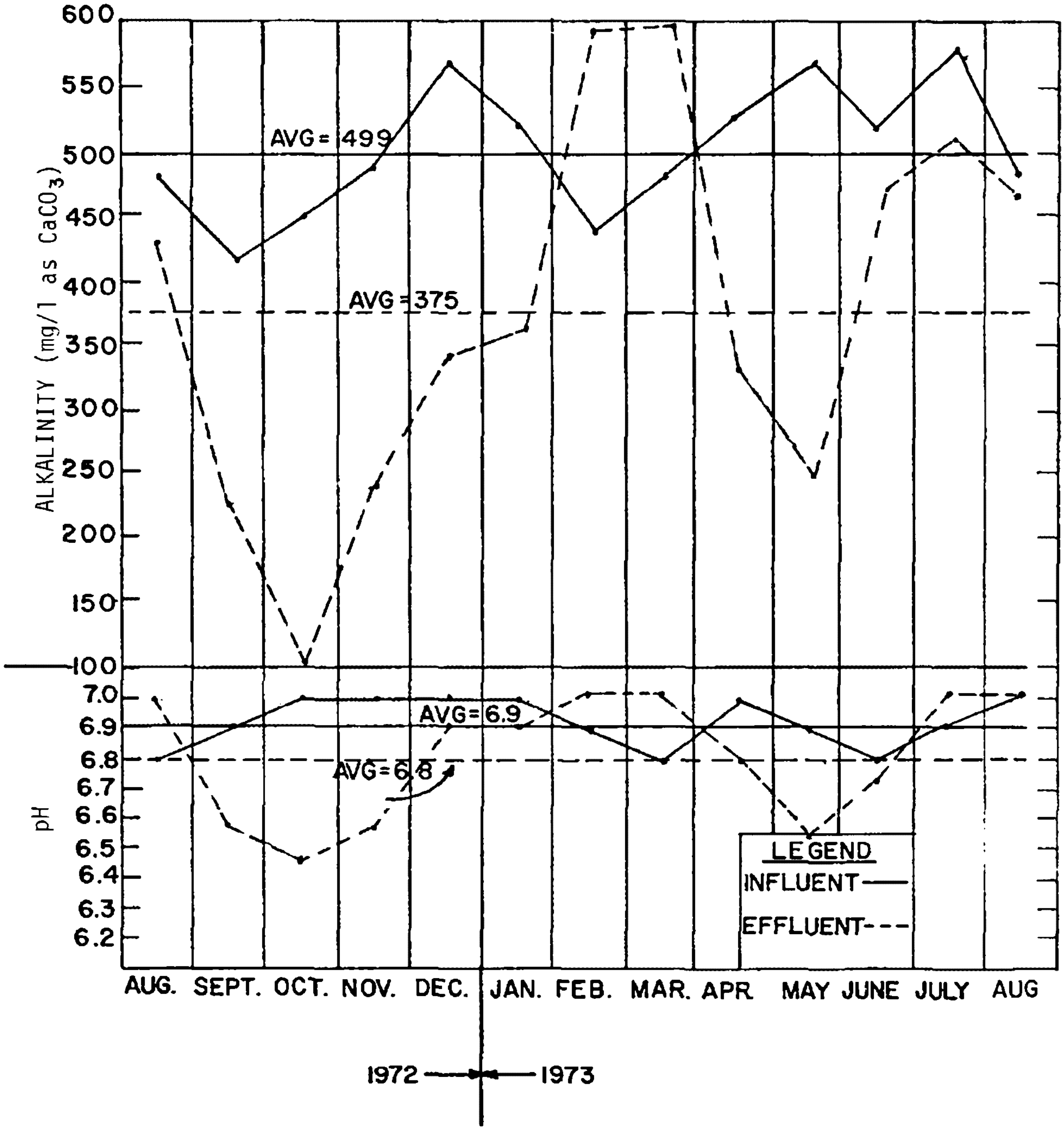


Fig. 30. Monthly variation of pH and alkalinity in diffused air digester influent and effluent

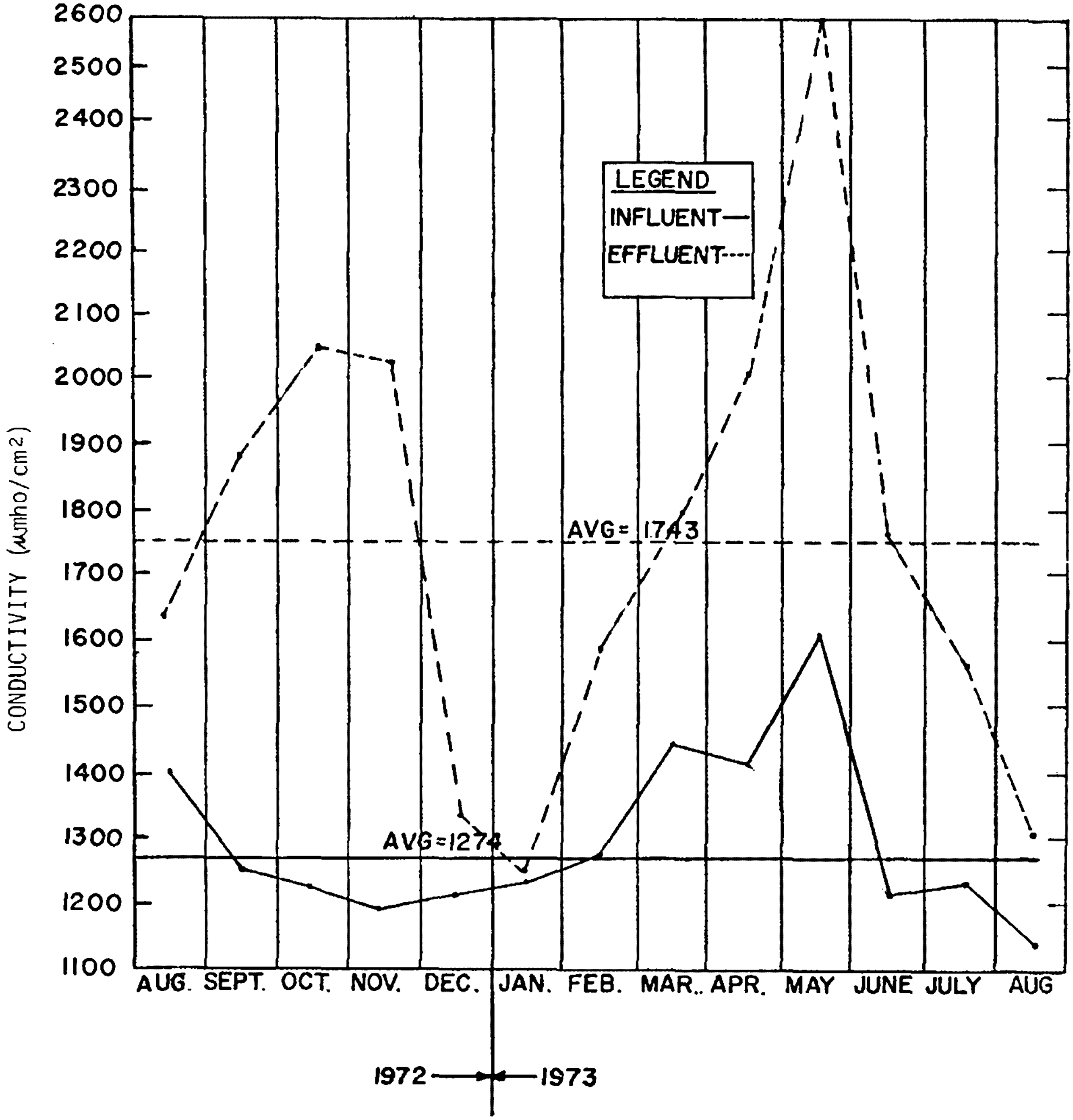


Fig. 31. Monthly variation of conductivity in diffused air digester influent and effluent

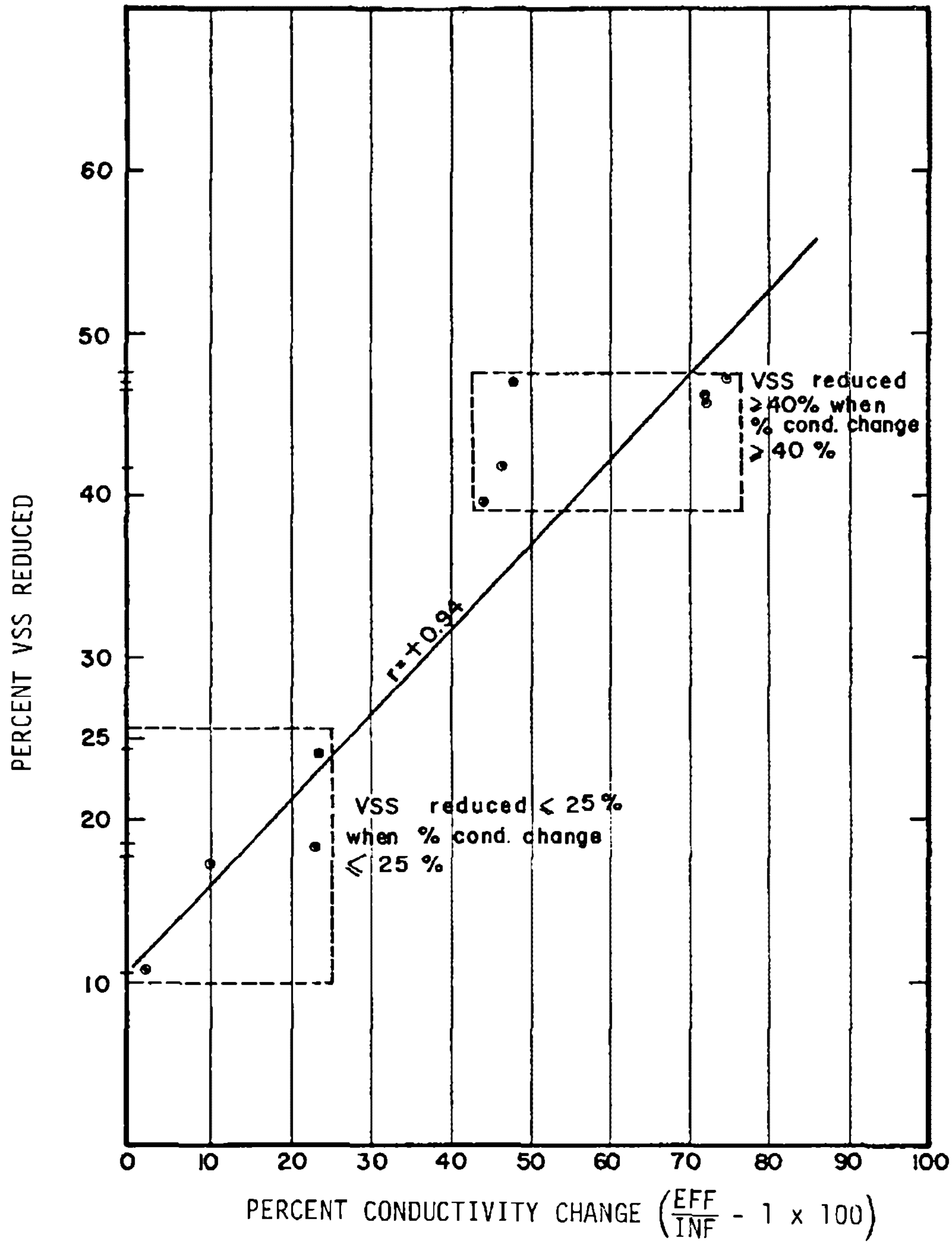


Fig. 32. Percent VSS reduction versus percent conductivity change in diffused air digester

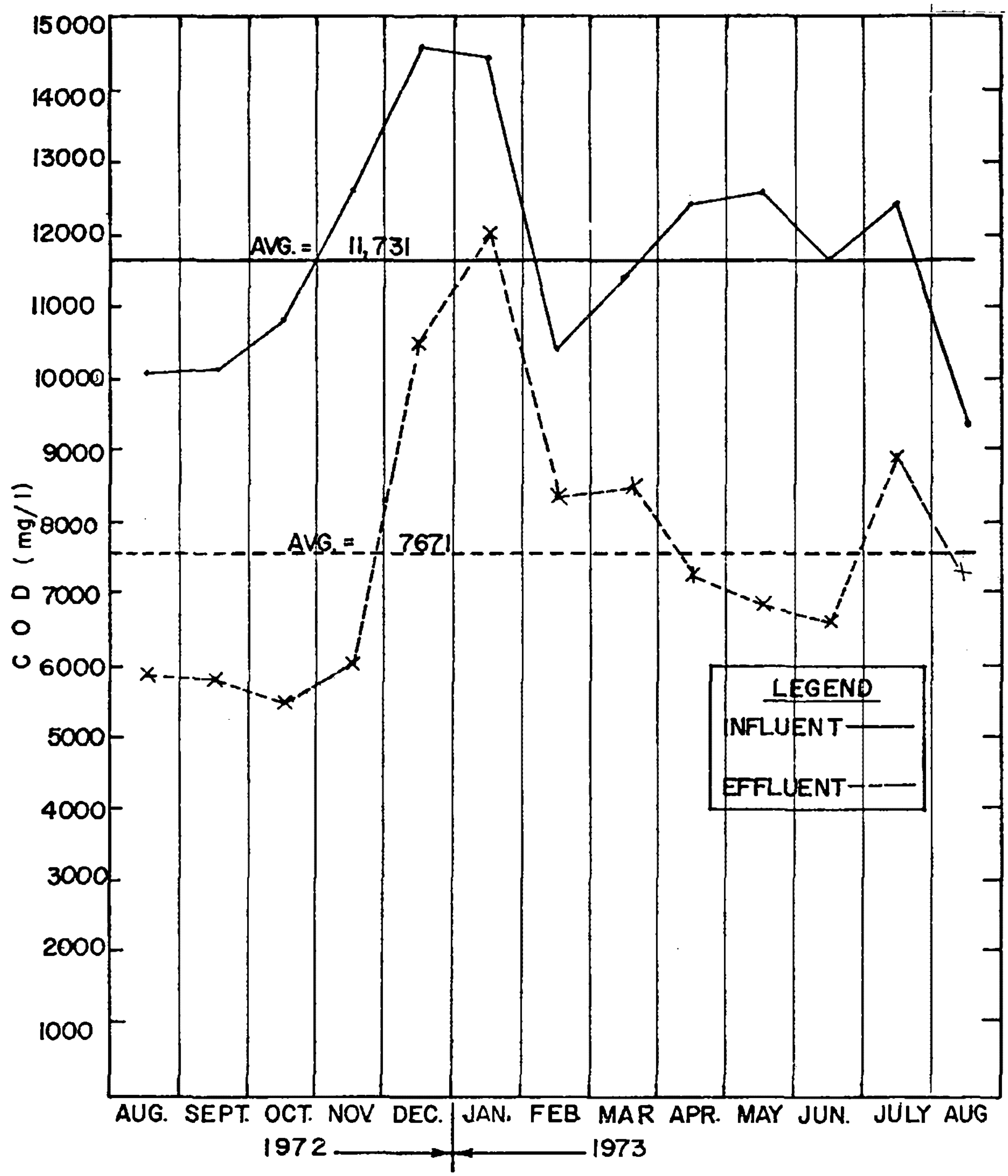


Fig. 33. Monthly variation of COD influent and effluent in diffused air digester

the monthly variation in COD concentration between influent and effluent. The decline in COD was 34.6% and compared well with a 32.4% reduction for VSS. The COD reduction was slightly greater than VSS reduction, as dissolved volatile solids are also oxidized during the aerobic stabilization process.

Phosphate

No correlation between VSS reduction and phosphate removal was observed. Figure 34 indicates that the percent change between influent and effluent averaged less than 1%. No significant changes in phosphorous uptake or release to the digester effluent occurred. Phosphorous was obviously not a limiting factor in the growth and reproduction of the aerobic digester microorganisms.

Summary of Physical and Chemical Laboratory Data

On the basis of changes that occurred between the influent and effluent (Table 4) the variables measured may be classified into three groups. In the first group, there was no correlation between influent and effluent differential and the degree of aerobic digestion. Phosphate was the only variable in this group. In the second group, there was a positive correlation between the influent and effluent differential and the aerobic digestion rate. In this group were found total, volatile and fixed dissolved solids, conductivity, nitrates and ammonium. In the third group, there is a negative correlation between the influent and effluent differential and the aerobic digestion rate. This group included pH, alkalinity, TKN, COD, TSS and VSS. Figure 35 shows the trends of the three major groups as previously discussed.

Invertebrate Analysis

Samples of aerobic digester biomass were collected, immediately diluted (1:10) with plant effluent, and placed in a Sedgwick Rafter cell. Ten fields were counted for each sample at a magnification of 150x, and the numerical count (number x $10^6/l$) calculated. The numerical counts were in turn converted to a

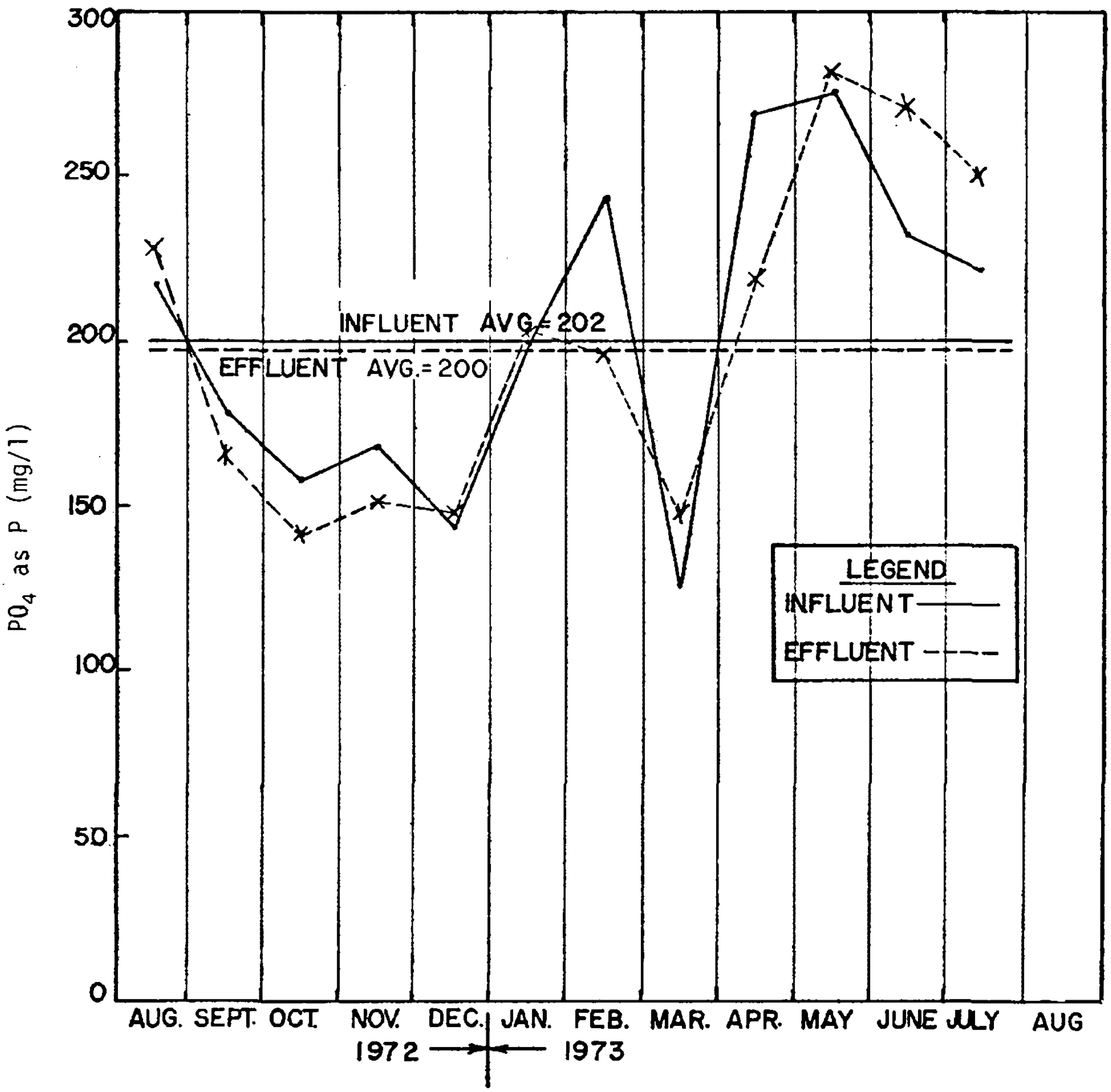


Fig. 34. Monthly variation of influent and effluent phosphate in diffused air digester

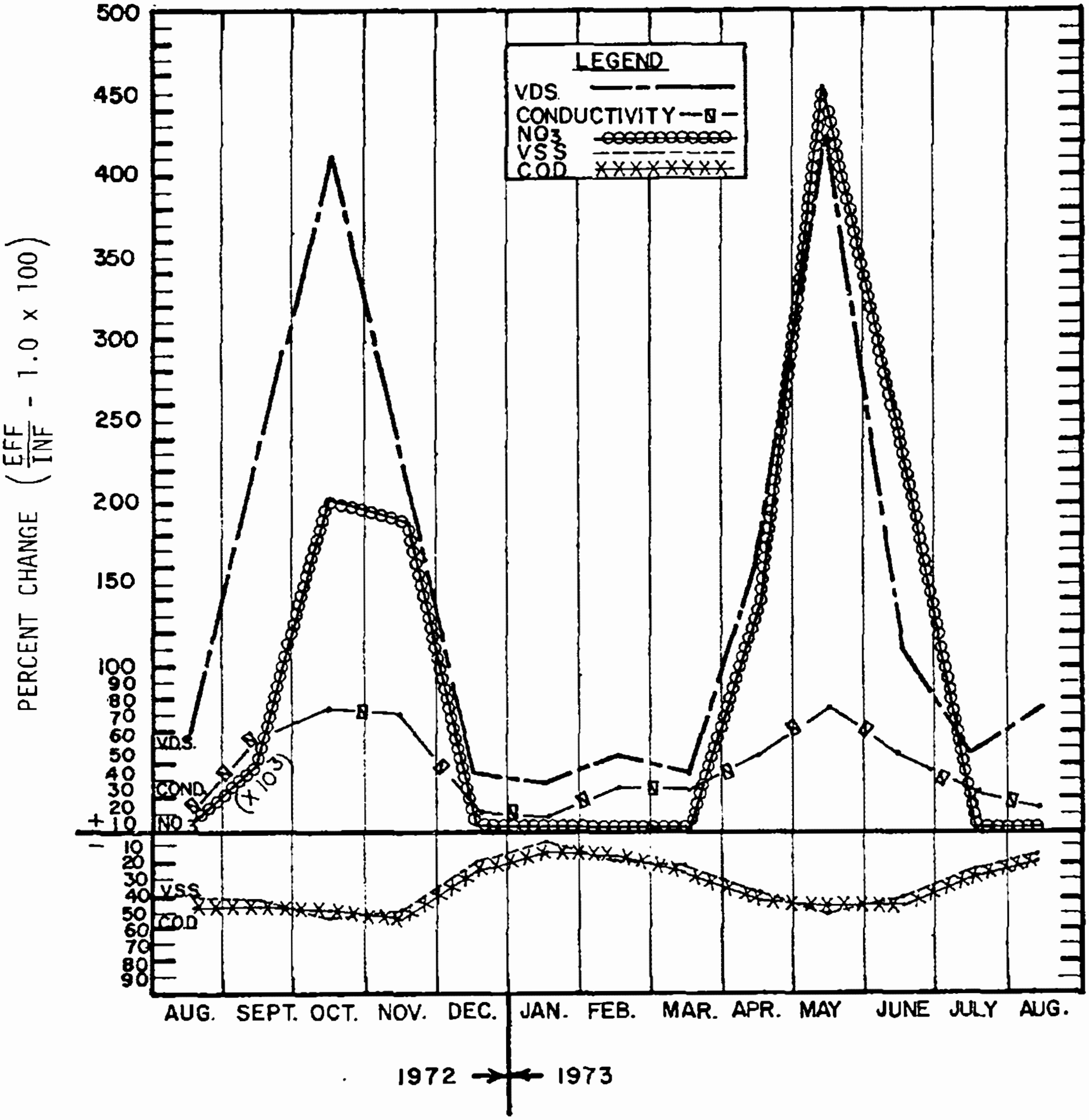


Fig. 35. Monthly variation of selected lab data (influent versus effluent) in diffused air digester

volumetric standard unit (VSU) using previously determined dimensions for each particular organism observed. The conversion factors from no./liter to VSU (mm^3/l) are listed in Appendix A. No attempt was made to include bacterial biomass in the enumerization because of size considerations. On a numerical basis, the smaller motile flagellates and ciliates comprised the great majority of organisms. When the numerical counts were converted to VSU, rotifers were found to comprise the great bulk of the invertebrate biomass. Table 8 summarizes the invertebrate biomass VSU data for the period August 1972 - August 1973. Table 9 analyzes the data in Table 8 with the organisms in each of the six major taxonomic groups observed listed as a percent of the total VSU. In Table 10 the invertebrate VSU data is analyzed as a percent of the VSS under aeration.

Changes in invertebrate populations appear to be related to environmental stresses, particularly temperature change and solids loadings. During August - November 1972, when temperatures were above 22°C and volumetric loadings were less than 1.6 kg VSS/m^3/day (0.1 lb VSS/ft^3/day), invertebrate diversity was high with the rotifer population assuming nearly half of the total dry weight biomass. During December 1972 when loadings increased to 3.0 kg VSS/m^3/day (0.187 lb VSS/ft^3/day) and temperature declined to 16°C, rotifers disappeared and ecological diversity declined. During this same period the percentage of flagellates and ciliates increased dramatically. Amoeba disappeared with the disappearance of rotifers and reappeared in May 1973, with the reappearance of rotifers. Nematodes were absent during most of the test period with the exception of the period May - June 1973 when several nematodes were observed. The calculated dry weight of total invertebrate biomass as a percent of the VSS under aeration (Table 10) approached a maximum of 54% during November 1972 and dropped to a low of less than 3% during April of 1973.

The highest VSS reductions were observed to occur during those months when invertebrate organisms comprised a significant fraction of the VSS under aeration. No one group of organisms was found to be an absolute indicator of ecosystem performance, but the rotifer population appeared to have the most significant correlation with VSS reduction (Figure 36). The coefficient of correlation between the rotifer population and the percent VSS reduced was very high +0.87. Figure 36 shows that the relationship between the percent VSS reduced and the total invertebrate biomass had a lower coefficient of correlation

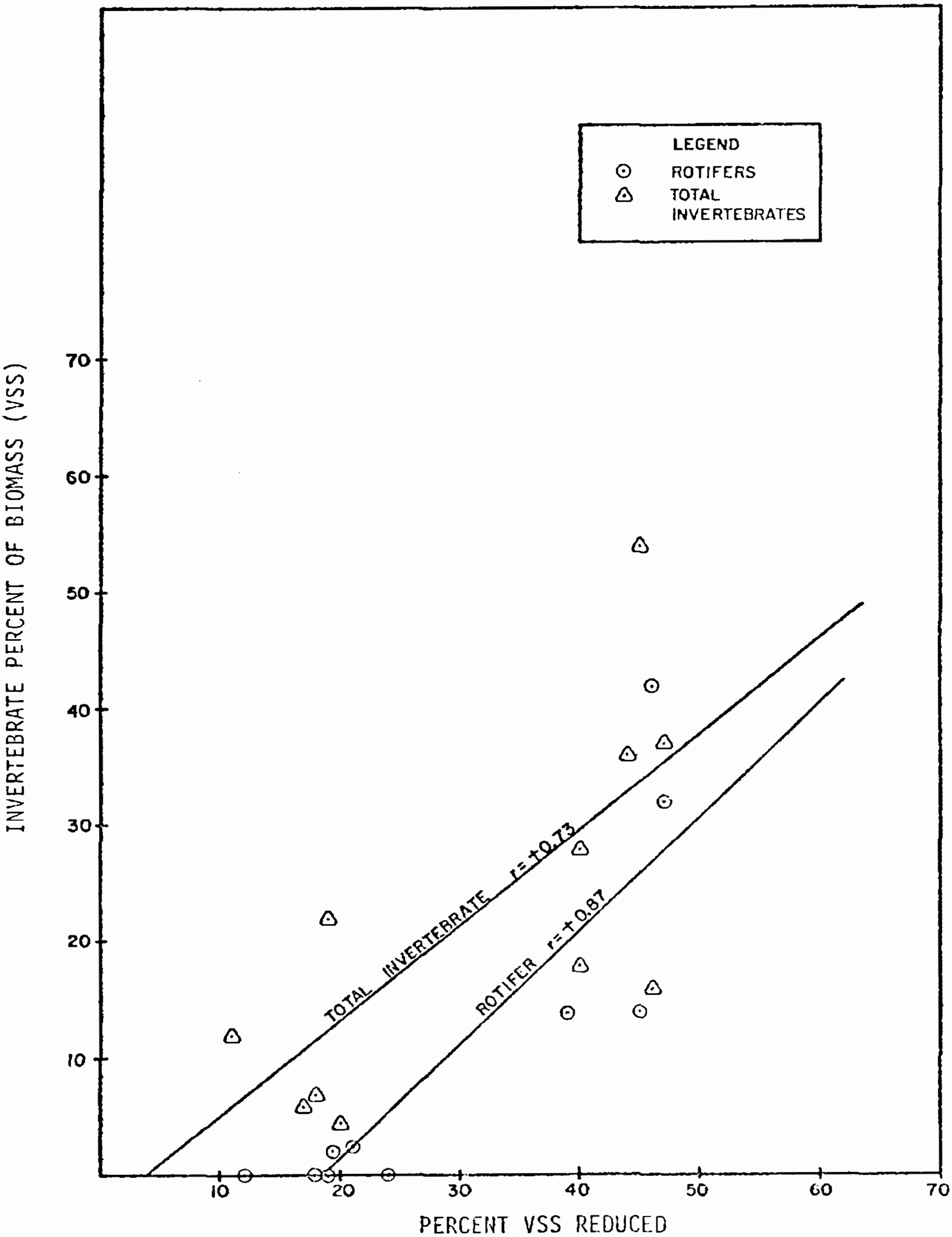


Fig. 36. Total invertebrates and rotifer fraction of biomass versus percent VSS reduced

Table 8. Monthly variation of invertebrate biomass in diffused air digester (volumetric standard units - g/l wet weight)

TAXONOMIC GROUP / MONTH	FLAGELLATE	MOTILE CILIATE	SESSILE CILIATE	ROTIFER	AMOEBA	NEMATODE	TOTAL ORGANISMS
AUGUST 1972	0.40	0.94	0.17	12.50	.03	0	14.04
SEPTEMBER	0.22	0.29	0.24	20.80	.006	0	21.56
OCTOBER	0.30	1.00	0.50	14.60	.02	0	16.42
NOVEMBER	1.30	0.50	0.50	25.00	.10	0	27.40
DECEMBER	2.30	1.10	0.70	0	.08	0	4.18
JANUARY 1973	5.00	0.60	3.00	0	0	0	8.60
FEBRUARY	1.80	4.00	5.00	0	0	0	10.80
MARCH	0.90	2.50	0.80	0	0	0	4.20
APRIL	0.30	0.70	0.80	0	0	0	1.80
MAY	0.72	0.16	0.35	8.30	.12	.03	9.68
JUNE	0.45	1.00	0.36	8.30	.05	.03	10.19
JULY	0.34	0.64	1.02	1.16	.05	0	3.21
AUGUST	0.62	1.72	0.75	1.56	.06	0	4.71
AVG.	1.13	1.17	1.09	7.09	.04	.005	10.52

Table 9. Monthly variation of invertebrate biomass percent distribution in diffused air digester (VSU basis)

TAXONOMIC GROUP / MONTH		FLAGELLATE	MOTILE CILIATE	SESSILE CILIATE	ROTIFER	AMOEBA	NEMATODE	ECOLOGICAL DIVERSITY INDEX OBSV	/ TOTAL
AUGUST	1972	2.85	6.70	1.20	89.00	0.25	0	5/6	(0.83)
SEPTEMBER		1.02	1.35	1.11	96.47	0.05	0	5/6	(0.83)
OCTOBER		1.83	6.09	3.05	88.92	0.11	0	5/6	(0.83)
NOVEMBER		4.74	1.82	1.82	91.24	0.38	0	5/6	(0.83)
DECEMBER		55.02	26.32	16.75	0	1.91	0	4/6	(0.67)
JANUARY	1973	58.14	6.98	34.88	0	0	0	3/6	(0.50)
FEBRUARY		16.67	37.04	46.30	0	0	0	3/6	(0.50)
MARCH		21.43	59.52	19.05	0	0	0	3/6	(0.50)
APRIL		16.67	38.89	44.44	0	0	0	3/6	(0.50)
MAY		7.44	1.65	3.62	85.74	1.24	0.31	6/6	(1.00)
JUNE		4.42	9.81	3.53	81.45	0.49	0.30	6/6	(1.00)
JULY		10.59	19.94	31.78	36.14	1.55	0	5/6	(0.83)
AUGUST		13.16	36.52	15.92	33.12	1.28	0	5/6	(0.83)
AVG.		16.46	19.43	17.19	46.31	0.56	0.05	-	(0.74)

Table 10. Monthly variation of invertebrate biomass as a percent of VSS in diffused air digester

TAXONOMIC GROUP / MONTH	FLAGELLATE	MOTILE CILIATE	SESSILE CILIATE	ROTIFER	AMOEBA	NEMATODE	TOTAL PERCENT OF VSS	VSS INV. (g/l)
AUGUST 1972	.8	1.86	.34	24.70	.06	0	27.75	5.06
SEPTEMBER	.45	.60	.49	42.80	.01	0	44.36	4.86
OCTOBER	.67	2.24	1.12	32.74	.04	0	36.82	4.46
NOVEMBER	2.57	.99	.99	49.41	.20	0	54.15	5.06
DECEMBER	3.22	1.54	.98	0	.11	0	5.85	7.14
JANUARY 1973	6.90	.83	4.14	0	0	0	11.86	7.25
FEBRUARY	3.09	6.86	8.58	0	0	0	18.52	5.83
MARCH	1.42	3.96	1.27	0	0	0	6.65	6.32
APRIL	.48	1.12	1.28	0	0	0	2.89	6.23
MAY	1.19	.26	.53	13.67	.20	.05	15.95	6.07
JUNE	.78	1.74	.63	14.46	.09	.05	17.75	5.74
JULY	.47	.89	1.42	1.62	.07	0	4.47	7.18
AUGUST	1.14	3.15	1.37	2.86	.11	0	8.63	5.46
AVG.	1.73	2.00	1.78	14.02	.07	0.008	19.67	5.90

+0.73 than for rotifers only. Changes in taxonomic group population densities are depicted in Figure 37. In order to convert the wet weight volumetric standard units listed in Table 8 to the total organism percent of VSS in Table 10, the invertebrate counts were converted to a dry weight basis by assuming that the biomass has the density of water with approximately 10% of the wet weight being equivalent to the dry weight.

The highly significant correlation between rotifer VSU and aerobic digester performance helps to explain a major difference between aerobic and anaerobic digestion systems. In the anaerobic ecosystem the dominant organisms are bacteria (volatile acid and methane producers), whereas in the aerobic ecosystem higher trophic levels of organisms consume lower forms, e.g. protozoa feed on bacteria and in turn are fed upon by the metazoan rotifers. In the aerobic system energy is dissipated as heat, whereas in the anaerobic system most of the energy is lost as carbon dioxide and methane. In the aerobic system, the newly synthesized biomass has virtually the same VSS/TSS ratio as the biomass originally loaded to the system. Autotrophic organisms in the aerobic system can use the waste CO_2 to produce new biomass. In the anaerobic system, the resynthesis rate is lower than in the aerobic system with consequent greater decline in the VSS/TSS ratio of the residue.

Bacterial Reductions

Figure 38 compares aerobic and anaerobic bacterial reductions versus detention time in the digester. The diffused air digester data represents optimal temperature conditions at an SRT of 8 days. The anaerobic digester data was obtained from a neighboring treatment plant (Denver Northside anaerobic digesters) during 1971 when SRT averaged 28 days. At an equivalent SRT (8 days) the anaerobic total bacteria count declined by only 25% (10^8/ml) while the aerobic total bacterial count dropped by 97% (10^5/ml). If bacteria were the only life forms in both systems, one would expect a significantly greater ratio of active mass/VSS in the anaerobic system after 8 days SRT.

Analysis of ATP as a measure of active biomass did not show any significant difference in the ATP/VSS ratio between the two systems.

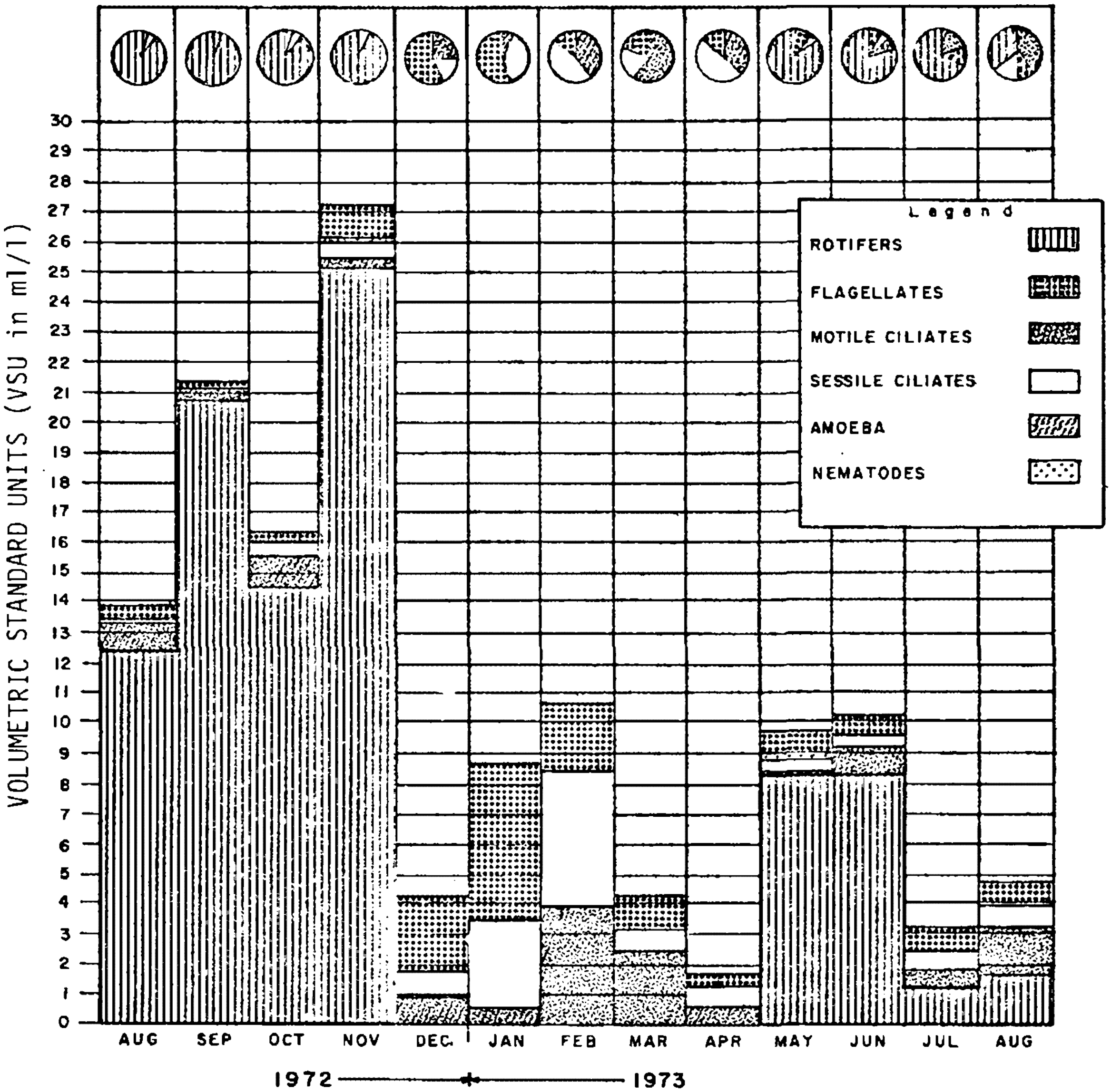


Fig. 37. Monthly variation of invertebrate biomass (VSU) in diffused air digester

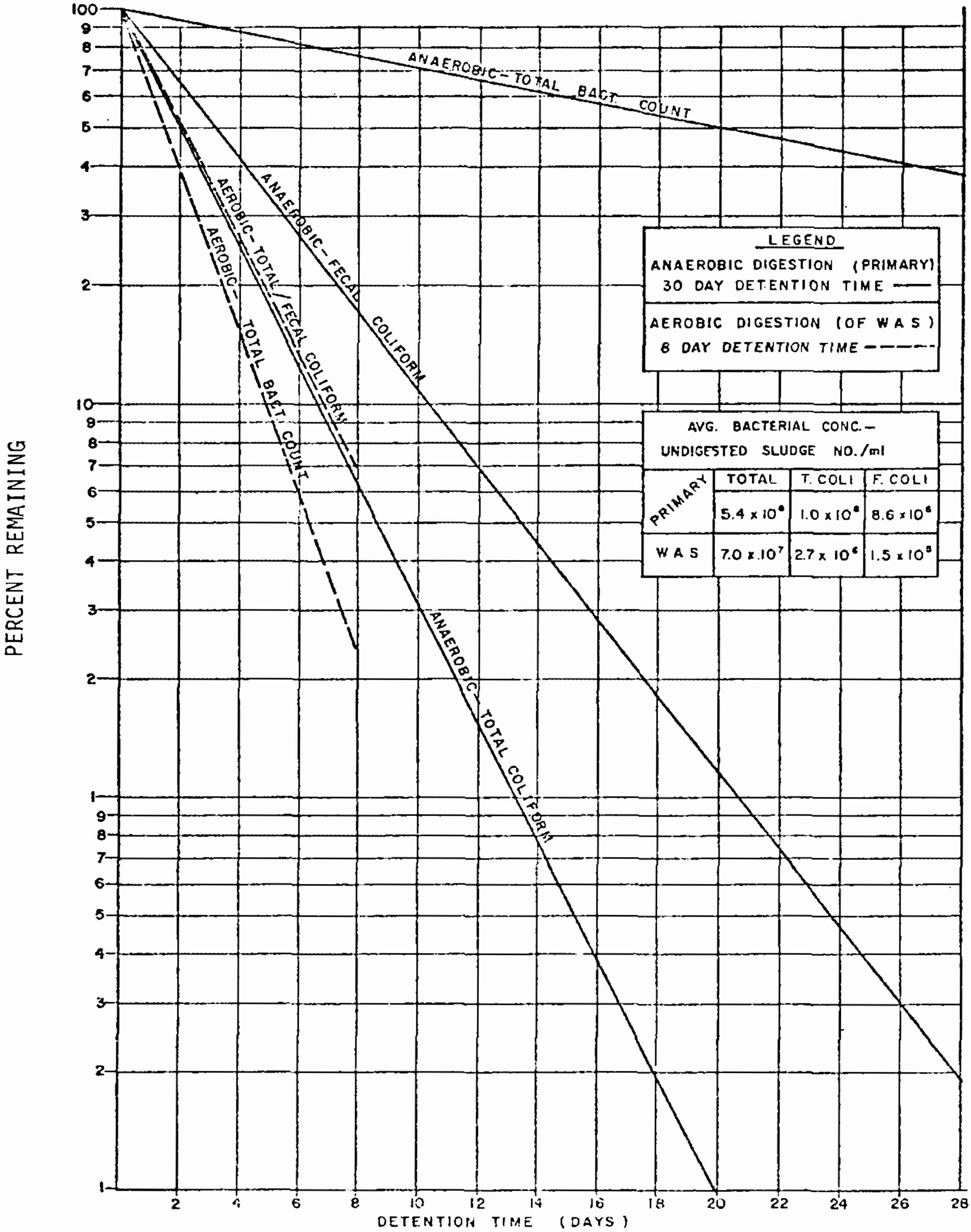


Fig. 38. Aerobic and anaerobic bacterial reduction versus detention time in digester

The concentration of ATP as determined by the luciferase tris-buffer extraction method (10) was 0.34 mg/l for the aerobic digester effluent and 0.60 mg/l for the anaerobic digester effluent. The VSS concentration of the aerobic sludge was 6.0 g/l versus 15.0 g/l for the anaerobic sludge. The ratio of ATP/VSS x 10^6 was therefore 58 for the aerobic sludge and 40 for the anaerobic sludge. The fact that the aerobic ATP/VSS ratio was greater than the anaerobic ratio can be explained on the basis of invertebrate ATP being significantly higher in the aerobic system. As previously discussed, data in Table 10 indicated that invertebrate biomass in the aerobic digester could exceed 50% of the VSS under aeration on a dry weight basis.

Fecal Coliform Bacteria

The concentration of fecal coli in the WAS fed to the aerobic digester was found to range between 6 and 50 x 10^6/ml, averaging 14.2 x 10^6/ml (Table 3). Fecal coli in the aerobic digester effluent ranged between 0.5 and 17.3 x 10^6/ml, averaging 3.6 x 10^6/ml. Fecal coli reductions ranged between 13.5% in January 1973 and 97.1% in September 1972. As temperature declined and organic loadings to the system increased, fecal coli reductions tended to decline.

Comparison of Aerobic and Anaerobic Stabilization

When Metro activated sludge is anaerobically digested for thirty days, the VSS/TSS ratio is reduced from approximately 80% to 60%. The amount of carbon lost from the anaerobic digester as methane and carbon dioxide is greater than the carbon dioxide lost from the aerobic system. When Metro WAS is aerobically digested for thirty days, the VSS/TSS ratios typically decline by less than 10% from approximately 80% to 72%. The concept "stabilization" must therefore be operationally defined in relation to biodegradation and odor potential particularly when digested sludges are to be disposed of on land.

If aerobically stabilized sludge with a volatile solids residue of about 76% is loaded to an anaerobic digester (SRT = 18 days) the VSS/TSS ratio can be further reduced to 62% (Figure 39).

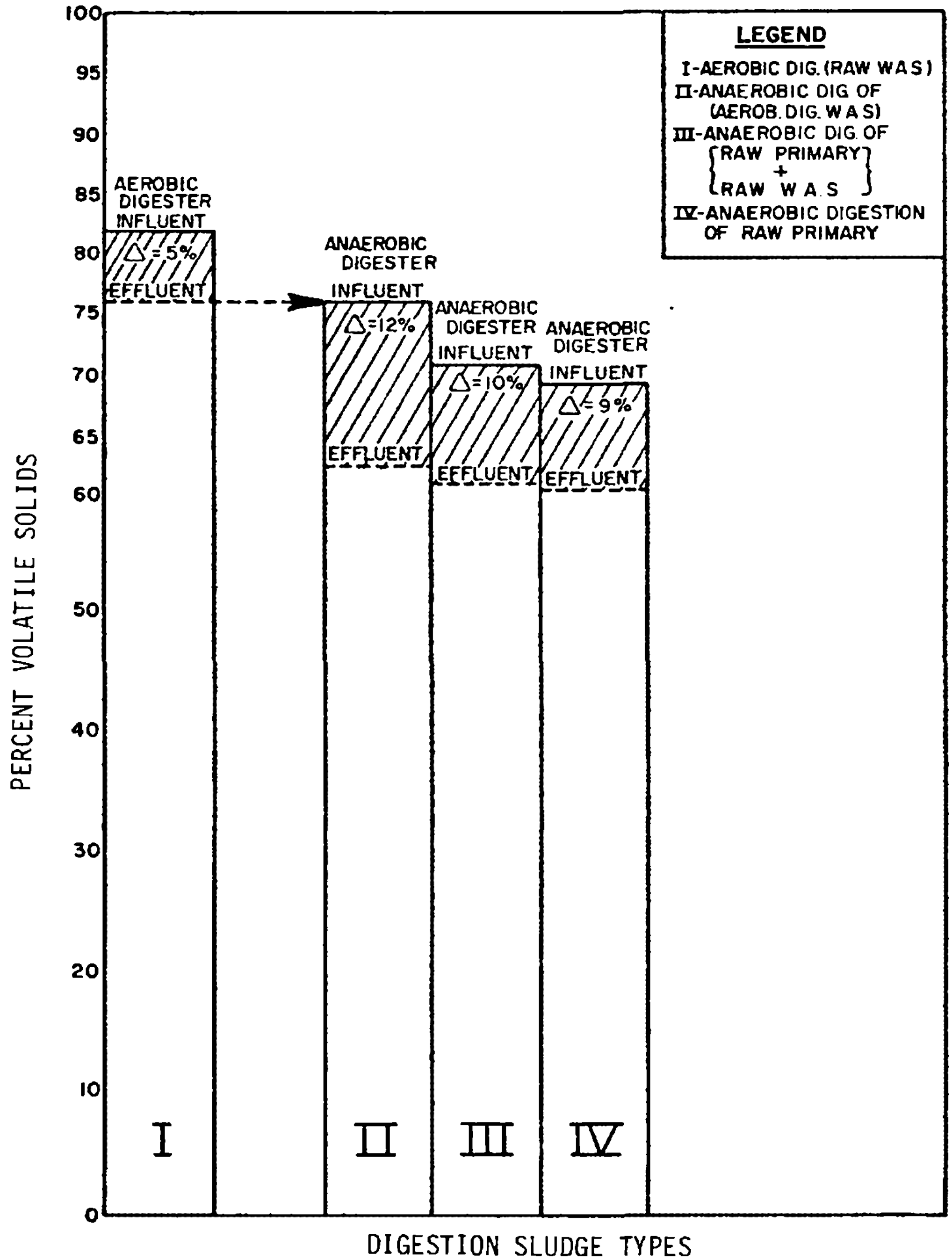


Fig. 39. Percent volatile solids reduction under aerobic and anaerobic conditions

This "double digested" material can be spread on land without fear of subsequent odor problems which might develop if the sludge was spread too heavily on land or otherwise allowed to go septic. This double digested sludge is approximately equivalent to the end product obtained after 20 days of anaerobically digesting primary sludge. Figure 40 contrasts the quality of aerobic and anaerobic digester supernatants. Metro aerobically digested supernatant recycle loadings are much less concentrated than anaerobic digestion supernatants from the neighboring Denver Northside plant.

A comparison of aerobic digester supernatant quality with anaerobic digester supernatant from a Metro pilot plant operated during 1973 indicated that COD, TKN, and NH_4 concentrations in the aerobic supernatant averaged less than 15% of the anaerobic concentrations. The BOD and TSS concentration in the aerobic supernatant averaged less than 10% of the anaerobic concentration. Figure 41 shows the monthly variations in the diffused air digester supernatant quality for the period February - August 1973.

Odor Panel Results

The most important indicator of sludge stability from an aesthetic viewpoint is odor. In order to define this problem quantitatively, a seven person panel (composed of five male and two female Metro staff personnel) was formed to periodically monitor the odor potential of a 190 litre (50 gal) sample spread over a 0.93 m^2 (10 ft^2) plot.

The panelists individually listed their reactions based on the following scale:

- 0 - Not Detectable
- 1 - Very Faintly Detectable
- 2 - Detectable - Not Objectionable
- 3 - Detectable - Objectionable
- 4 - Detectable - Very Objectionable

On October 25, 1972 three separate sludge test plots were prepared consisting of:

1. Anaerobically Digested Primary Sludge

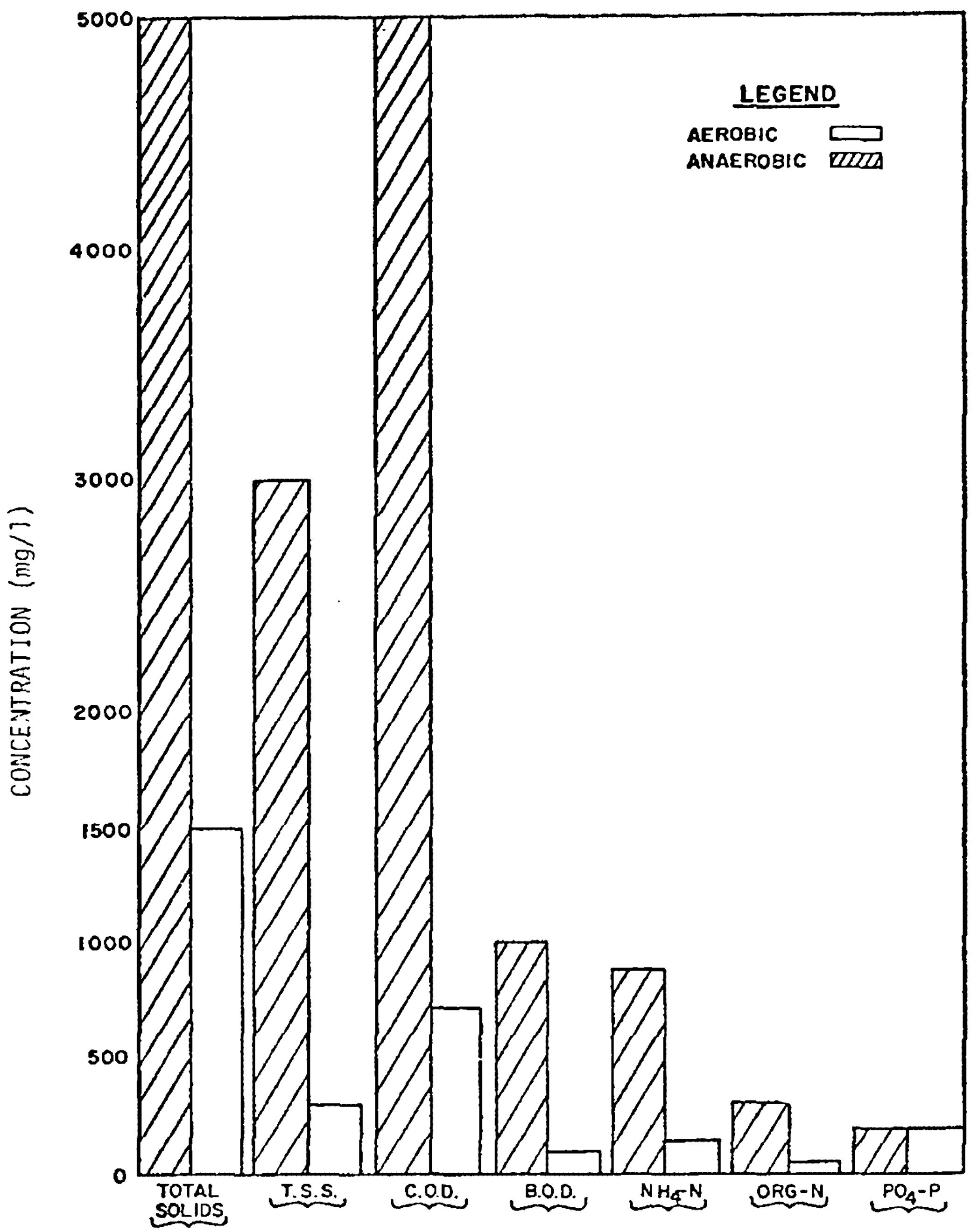


Fig. 40. A comparison of supernatant quality under aerobic and anaerobic conditions

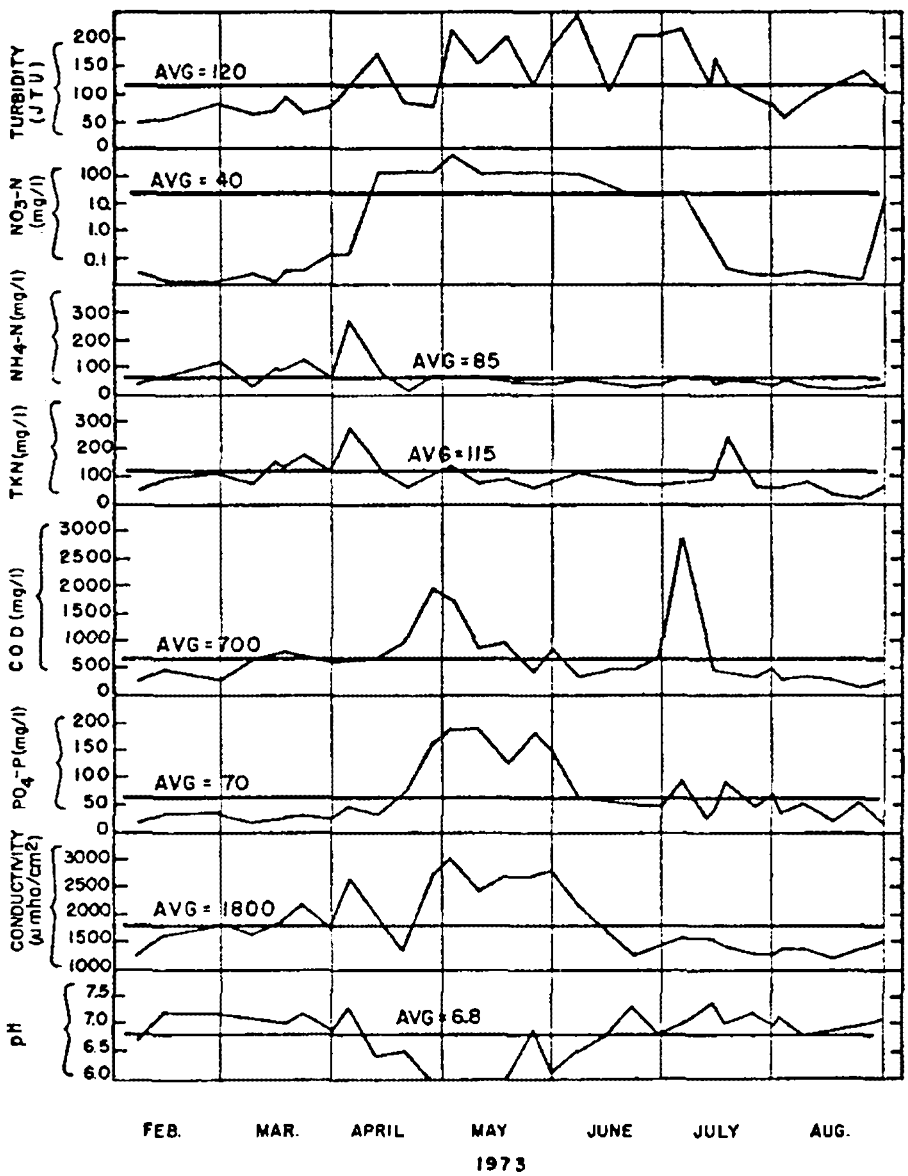


Fig. 41. Diffused air digester supernatant quality monthly variation

2. Aerobically Digested Sludge

3. Mixture (1:1 Ratio) of Sludges 1 and 2

Figure 42 summarizes odor results for the three sludge mixtures during a twenty-eight day period. The aerobically digested sludge (VSS/TSS ratio of 75%) had the least offensive odor initially. When this sludge was mixed in a 1:1 ratio with anaerobically digested sludge (VSS/TSS ratio of 60%) however, a definitely objectionable odor occurred. The resultant "pig pen" odor was so objectionable that large scale plans to land spread a mixture of aerobically and anaerobically digested sludges had to be cancelled.

These results, which were repeated both indoors and outdoors, indicated that the so called "non-biodegradable" fraction of the aerobically digested VSS can be utilized by a heterogeneous anaerobic bacterial culture. Thus offensive odors are a definite possibility if either aerobic or anaerobic sludge residues have a VSS/TSS ratio above 60%.

Sludge Dewaterability

The major impetus for investigating the aerobic stabilization of waste activated sludge arose from the need to reduce handling and disposal costs. Although the existing solids handling unit processes at Metro included dissolved air flotation, vacuum filtration and land application, sand drying bed dewatering was also investigated, as this method is commonly used in small treatment plants. Specific resistance of sludges to vacuum filtration as determined from Buchner Funnel tests, indicated no significant difference in dewaterability between sludges before and after aerobic stabilization ($r_s=10^9$ sec^2/g) where SRT ranged between 3.1 and 13.4 days.

Vacuum filter leaf tests were run on dissolved air flotation thickened samples of influent and effluent from the test digester to obtain information on relative loading rates and chemical demand. Table 11 summarizes the filter leaf data, comparing relative performances based upon chemical cost ($/ton), filter cake (percent TS) and loading rates $kg/m^2/hr$ ($lb/ft^2/hr$). The results obtained indicate that for an equivalent chemical cost, better vacuum filter performance was obtained with the aerobically digested sludge. For example, on July 10, 1973

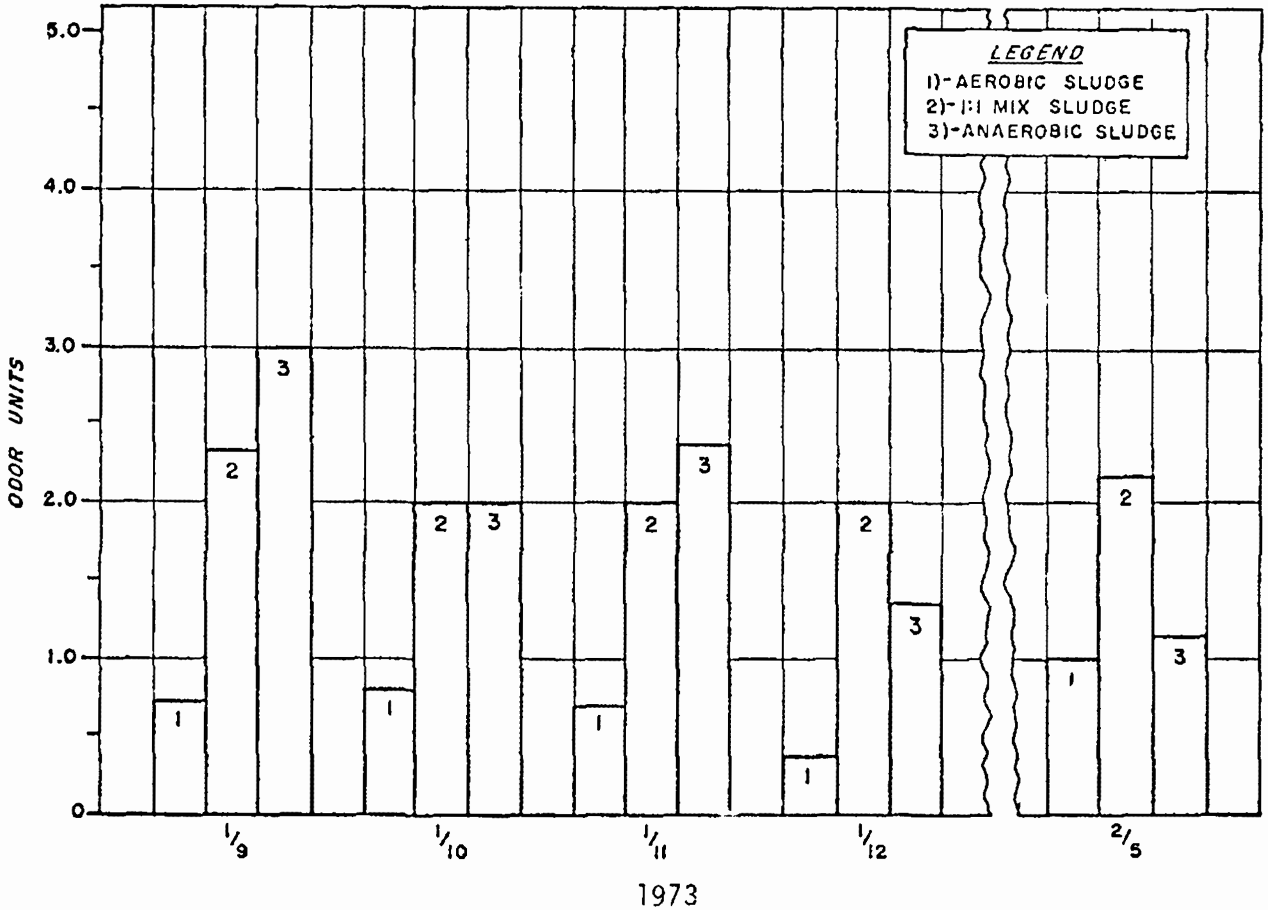


Fig. 42. Odor panel results for aerobic and anaerobic sludge

Table 11. Vacuum filter leaf test results of diffused air digester influent and effluent

DATE	SAMPLE	PERCENT TS		CONC. FACTOR	PERCENT CHEMICALS (1)			CHEMICAL COST (1) $/ton	LOADING RATE (3) (lb/ft^2/hr	VACUUM FILTER PERFORMANCE (2)
		Feed	Cake		$FeCl_3$	Lime	Total			
3/27/73	EFF	4.1	15.1	3.7	7.4	26.8	34.2	14.10	2.1	1.8
		"	15.0	3.7	6.2	22.4	28.6	11.80	1.9	1.7 *
		"	13.6	3.3	9.9	33.6	43.5	18.30	2.5	2.2
7/10	INF	4.6	10.1	2.2	5.0	4.9	9.9	6.23	0.5	5.7
		"	11.9	2.6	5.0	9.9	14.9	7.48	0.9	3.2 *
		"	13.1	2.8	9.9	19.8	29.7	14.85	1.9	2.8
	EFF	4.6	10.2	2.2	4.9	4.9	9.8	6.13	0.6	4.6
		"	12.2	2.7	4.9	9.8	14.7	7.35	0.9	3.0
		"	13.3	2.9	9.9	19.7	29.6	14.83	3.0	1.7 *
8/8	INF	4.9	12.9	2.6	3.1	6.1	9.2	4.63	0.8	2.2
		"	13.5	2.8	5.1	10.2	15.3	7.65	1.3	2.1
		"	15.4	3.1	8.1	16.3	24.4	12.18	3.0	1.3 *
	EFF	4.7	12.0	2.6	4.3	8.6	12.9	6.45	1.0	2.5
		"	13.2	2.8	5.3	10.8	16.1	8.00	1.4	2.0
		"	14.0	3.0	8.6	17.2	25.8	12.90	2.9	1.5 *
8/22	INF	4.0	12.9	3.2	6.5	12.9	19.4	9.73	0.5	6.1
		"	14.9	3.7	9.3	18.6	27.9	13.95	1.1	3.1 *
	EFF	5.1	11.8	2.3	4.5	8.9	13.4	6.73	1.4	2.1
		"	12.3	2.4	5.2	10.3	15.5	7.78	1.6	2.0
		"	14.3	2.8	6.7	13.3	20.0	11.70	2.5	1.7 *

(1) $FeCl_3$ = $100/Ton; Lime = $25/Ton * optimal dose

(2) $\frac{\$/\text{Ton}}{\text{Conc. Factor} \times \text{Load Rate}}$ (best performance = lowest value)

(3) lb/ft^2/hr x 4.88 = kg/m^2/hr

the vacuum filter production rate after aerobic digestion was 50% greater at an equivalent chemical dosage than before aerobic digestion.

In order to obtain additional data concerning the effects of aerobic digestion on dewatering characteristics of the sludge, four model size sand drying beds were built according to the description of Randall and Koch.[11] To determine the relative dewaterability of aerobic and anaerobic sludge mixtures, 20 liters of each sludge sample were applied to separate sand filters and cumulative filtrate volumes recorded for 7.5 days (180 hours). The 180 hour drainage time was chosen as a performance standard and calculated on the basis of volume filtered/ volume applied. Table 12 summarizes the results obtained. On a direct volumetric measurement basis, the filtration rates of the aerobically digested and undigested WAS sludges were approximately equal. Anaerobically digested sludge drained slowest, while the 1:1 volumetric ratio of aerobic and anaerobic sludges showed intermediate drainability. Aerobically digested sludge drained three times as fast as anaerobically digested sludge on a volumetric basis. Since a waste treatment plant must process a given amount of sludge mass per day, the comparison of drainage rates should be made on a mass basis. When this comparison is made, the anaerobically digested sludge was found to drain 2.5 times faster than the aerobically digested sludge. Table 13 summarizes the effect of VSS loading rates on the relative drainability of aerobically digested and undigested sludges. On a volumetric comparison basis, there is little difference in drainability between aerobic digester influent and effluent. On a solids weighted basis, the undigested sludge drains 20% faster than the digested sludge. Although the aerobic digester effluent appears to drain slower on a weight basis, there is less mass to filter due to mass reduction in the digester.

The thickening of aerobically digested sludge by air flotation was affected by the particle surface area available for cationic polymer conditioning. An inverse relationship was observed between polymer demand during air flotation and sludge loading rates to the aerobic digester. The effect of varying loading rates on dissolved air flotation polymer demand is illustrated in Figure 43.

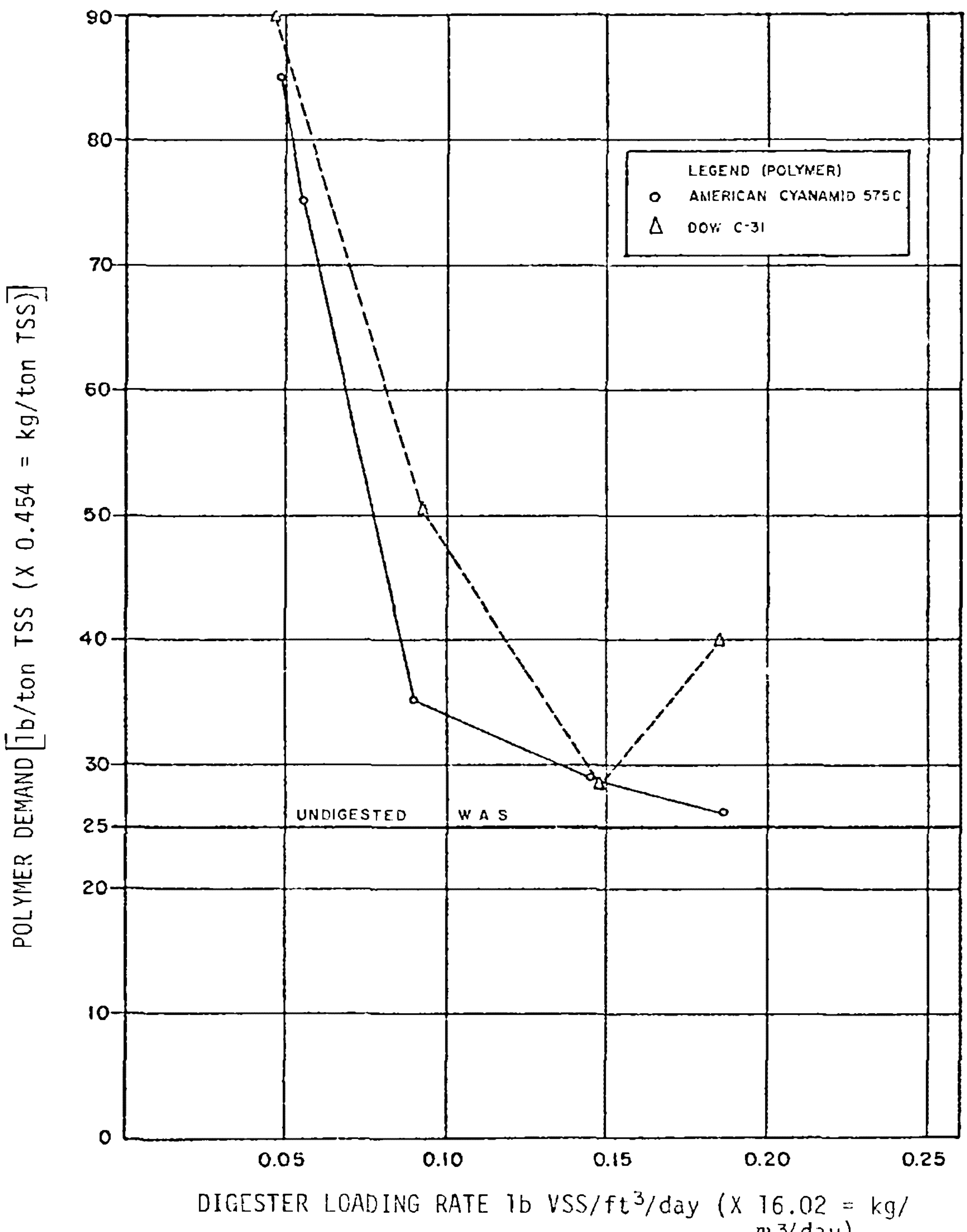


Fig. 43. Air flotation polymer demand versus diffused air digester loading rate

Table 12. A comparison of sand filtration results with aerobic and anaerobic digested sludge

DATE	FILTERED RATIO (1)				RATIO $\frac{AEROB.}{ANAER.}$ (3)	
	A. DIGESTION INF	A. DIGESTION EFF	ANAEROBIC EFFLUENT	MIXED EFFLUENT (2)	VOLUMETRIC BASIS	MASS BASIS
1/3/73	0.65	0.61	-	-	-	-
1/17	0.60	0.69	-	-	-	-
1/31	0.630	0.650	-	-	-	-
2/13	0.510	0.595	0.240	0.501	2.48	0.32
3/19	0.615	0.615	0.270	0.450	2.28	0.31
4/19	0.445	0.755	0.315	0.650	2.40	0.29
5/9	0.685	0.600	0.125	0.075	4.80	0.65
5/29	0.650	0.735	0.110	0.360	6.68	0.91
6/8	0.650	0.740	0.0	0.300	-	-
6/19	0.660	0.735	0.300	0.540	2.45	0.31
6/29	0.590	0.715	0.290	0.495	2.47	0.31
7/9	0.625	0.690	0.325	0.550	2.12	0.35
7/24	0.700	0.705	0.355	0.605	2.00	0.26
8/2	0.690	0.690	0.240	0.425	2.38	0.31
8/13	0.745	0.740	0.0	0.115	-	-
AVG.	0.630	0.684	0.218	0.422	3.00	0.40

(1) $\frac{\text{volume filtrate collected @180 hrs}}{\text{volume digested sludge applied to sand filter}}$

(2) 1:1 ratio of aerobic and anaerobic digester effluent

(3) $\frac{\text{volume aerobic digester effluent filtrate}}{\text{volume anaerobic digester effluent filtrate}}$

Table 13. Effect of loading rate to diffused air digester on sand filtration rate (volume filtered/volume applied)

VSS LOADING (1) lb/ft^3/day	DIGESTER INFLUENT	DIGESTER EFFLUENT	VOLUMETRIC RATIO EFF/INF	VSS RATIO EFF/INF	MASS BASIS RATIO EFF/INF
.026	0.445	0.755	1.70	0.61	1.02
.078	0.668	0.668	1.00	0.51	0.51
.086	0.633	0.730	1.15	0.59	0.68
.140	0.718	0.715	1.00	0.82	0.82
.150	0.647	0.670	1.04	0.77	0.80
.187	0.598	0.636	1.06	0.86	0.91
AVG. -	-	-	1.10	-	0.79

(1) lb/ft^3/day x 16.02 = kg/m^3/day

Undigested WAS had an average cationic polymer demand of 11.4 kg/ton (25 lb/ton). Average daily production of WAS before aerobic digestion was 40 tons/day. Cationic polymer cost at Metro without aerobic digestion averaged $91,000/year. When aerobic digestion of WAS was initiated at Metro, it was found that polymer demand increased from 13.7 kg/ton (30 lb/ton) at a loading to the digester of 1.6 kg VSS/m^3/day (0.10 lb VSS/ft^3/day) to 41.1 kg/ton (90 lb/ton) at a loading of 0.8 kg VSS/m^3/day (0.05 lb VSS/ft^3/day). If the optimal loading to the digester of 1.6 kg VSS/m^3/day was maintained, 16 tons VSS/day were digested leaving a residue of 24 tons VSS/day requiring air flotation at a cost of $66,000/year. When the sub-optimal loadings to the digester of 0.8 kg VSS/m^3/day were maintained 18 tons VSS/day were digested leaving a residue of 22 tons/day requiring air flotation at a cost of $181,000 per year. Strict control of loadings to the aerobic digester must be maintained if the advantages of mass reduction are not to be lost in the subsequent air flotation thickening process.

EXPERIMENTAL RESULTS - PURE OXYGEN BATCH TESTS

Batch Test No. 1

The first pure oxygen batch test with concentrated WAS (5.1% TSS) was run between November 30 and December 20, 1972. Only one of the 6.8 m^3 (1800 gal) tanks was used to determine the mechanical and operational adequacy of the system. Three FAD diffusers were used in the single tank.

Experimental data for Batch Test 1 are presented in Tables 14, 15 and 16. Table 14 summarizes data from laboratory analysis, Table 15 presents average operating data and Table 16 indicates the calculated values for TSS and VSS reductions.

Cyclical variations in solids concentrations and calculated TSS and VSS reduction are evident. The sampling and laboratory analyses were checked to verify the accuracy of the analytical techniques. The methods were found to be accurate.

The cyclical results were attributed to fluctuations between soluble and insoluble VS and TS. Soluble VS and TS were not measured frequently enough in this batch test to verify this conjecture.

The sludge temperature increased from (19.4 ^oC) initially to a maximum value of (44.5 ^oC). This uncontrolled temperature increase may have been responsible for significant changes in microorganism populations during the test period. Installation of a water jacket heat exchanger was recommended to correct this situation. A leak in the sludge recirculation pump packing was noted on December 7, 1972 but not until approximately 15.3 cm (6 in.) of sludge had been lost from the system. A float measuring device was provided to accurately indicate liquid level for detection of this type of failure. The dissolved oxygen concentration remained below 1.0 mg/l for the first nine days, because of very high O_2 uptake rates (in excess of 200 mg/l/hr).

Table 14. Pure oxygen digester batch test no. 1 - laboratory data (mg/l unless other units indicated)

DATE	pH (Units)	CONDUCTIVITY µmho/cm²	SUSPENDED SOLIDS TSS	SUSPENDED SOLIDS VSS	DISSOLVED SOLIDS TDS	DISSOLVED SOLIDS FDS	DISSOLVED SOLIDS VDS	COD	PO_4	NITROGEN-N NO_3	NITROGEN-N NH_3	NITROGEN-N T K N	ALKALINITY (as $CaCO_3$)	FECAL COLI (no./ml)
11/30	6.5	1,090	51,300	44,400	2,220	1,464	756	82,200	1,130	<.01	136	3,730	2,460	1.8×10^7
12/1	6.6	1,270	42,500	37,700									2,420	
12/2	6.5	4,850	38,900	33,100									2,900	
12/3	6.8	5,310	37,200	30,800									3,380	
12/4	7.0	6,000	38,800	31,400									3,620	
12/5	7.1	6,060	45,200	37,200									3,970	
12/6	7.2	5,240	30,600	26,400									3,750	
12/7	7.2	6,292	24,600	20,000									3,690	
12/8	7.3	5,140	32,800	26,800									4,050	
12/9	7.3	6,410	20,400	17,000										
12/10	7.3	6,410	26,400	22,800										
12/11	7.6	7,660	28,200	22,400										
12/12	7.6	5,620	24,400	16,600	12,200	1,700	10,500						3,940	
12/13	7.6	5,880	28,200	22,200										
12/14	7.5	5,970	29,800	22,200										
12/15	7.2	5,150	N.A.	N.A.										
12/16	N.A.	N.A.	37,000	30,200										
12/17	7.1	8,040	33,200	24,800										
12/18	7.4	5,800	20,300	16,000									4,690	
12/19	7.3	9,190	25,400	18,000										
12/20	7.8	8,100	26,300	22,200	9,800	5,800	4,000	41,100	744	1.0	N.A.	3,540	5,490	$<2.0 \times 10^5$

Table 15. Pure oxygen digester batch test no. 1 - field data

DATE	AVERAGE D.O. (mg/l)	AVERAGE SLUDGE TEMP. (°F) (1)	AVERAGE O_2 UPTAKE mg/l/hr	mg/hr/g (VSS)
11/30/72	0.8	72 (initial 67°)	N.A.	N.A.
12/1/72	0.5	82	N.A.	N.A.
12/2	0.6	91	N.A.	N.A.
12/3	0.6	94	N.A.	N.A.
12/4	0.6	88	N.A.	N.A.
12/5	0.7	88	N.A.	N.A.
12/6	0.6	87	N.A.	N.A.
12/7	0.5	90	N.A.	N.A.
12/8	0.4	95	N.A.	N.A.
12/9	0.9	99	N.A.	N.A.
12/10	1.5	106	N.A.	N.A.
12/11	3.7	108 (high 112°)	N.A.	N.A.
12/12	13.3	97	34	2.05
12/13	16.9	94	36	1.62
12/14	17.7	92	52	2.34
12/15	2.0	91	52	6.67
12/16	8.2	91	54	1.79
12/17	11.5	89	39	1.57
12/18	2.7	90	44	2.75
12/19	2.6	90	47	2.61
12/20	2.8	90	61	2.75

(1) (°F-32) 5/9 = °C

Table 16. Pure oxygen digester batch test no. 1 - inventory mass reduction

DATE	LIQUID INVENTORY (lb) (1)	TSS (mg/l)	VSS (mg/l)	SOLIDS INVENTORY TSS (lb)(1)	SOLIDS INVENTORY VSS (lb)(1)	PERCENT MASS REDUCTION TSS	PERCENT MASS REDUCTION VSS
11/30/72	14276	51,300	44,400	732.4	633.9	--	--
12/1/72	14019	42,500	37,700	595.8	528.5	18.6	16.6
12/2/72	13983	38,900	33,100	543.9	462.8	25.7	27.0
12/3/72	13946	37,200	30,800	518.8	429.5	29.2	32.2
12/4/72	13873	38,800	31,400	538.3	435.6	26.5	31.3
12/5/72	13836	45,200	37,200	625.4	514.7	14.6	18.8
12/6/72	13800	30,600	26,400	422.3	364.3	42.3	42.5
12/7/72	13727	24,600	20,000	337.7	274.5	53.9	56.7
12/8/72	13690	32,800	26,800	449.0	366.9	38.7	42.1
12/9/72	13653	20,400	17,000	278.5	232.1	62.0	63.4
12/10/72	13617	26,400	22,800	359.5	310.5	50.9	51.0
12/11/72	13544	28,200	22,400	381.9	303.4	47.8	52.1
12/12/72	13507	24,400	16,600	329.6	224.2	55.0	64.6
12/13/72	13470	28,200	22,200	379.9	299.0	48.1	52.8
12/14/72	13434	29,800	22,200	400.3	298.2	45.3	52.9
12/15/72	NA	NA	NA	NA	NA	NA	NA
12/16/72	13361	37,000	30,200	494.4	403.5	32.5	36.3
12/17/72	13324	33,200	24,800	442.4	330.4	39.6	47.9
12/18/72	13287	20,300	16,000	269.7	212.6	63.2	66.5
12/19/72	13251	25,400	18,000	336.6	238.5	54.0	62.4
12/20/72	13241	26,300	22,200	347.5	293.4	52.5	53.7

(1) lb x 0.454 = kg

On December 12, 1973, DO concentration rose suddenly accompanied by a sudden drop in temperature to $32.8^{o}C$, and a drop in DO uptake rates. These three changes indicated that the initial high rate of metabolic activity had altered qualitatively, as well as quantatively on the twelfth day of the test.

The pH rose from an initial 6.5 to 7.6,then gradually declined to 7.1, and then increased again to a maximum of 7.8 on the final day. These fluctuations correlated with the increasing alkalinity (+223%) of the system. Volatile organic acids which can be easily driven off at the high temperatures encountered up to December 12, 1973 would account for this increase in alkalinity. Conductivity increased eight fold between initial and final sampling. The cyclical nature of this increase may be related to resynthesis of new bacterial biomass, utilizing metabolic intermediates. The VSS concentration declined by 50% after 20 days. This reduction was almost identical with that achieved at the end of 10 days. This cyclical phenomenon was observed in all of the subsequent pure O_2 batch tests. TDS and VDS increased more than four fold between the initial and final samples (+441% and +529% respectively). The COD reduction of 50% correlated well with the VSS reduction previously noted.

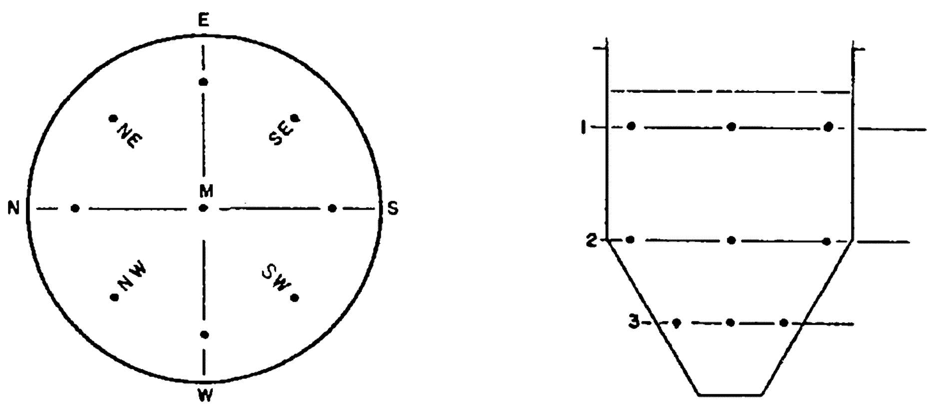
Nitrification did not occur to any substantial degree. The nitrifying bacteria may have been inhibited by the high temperature experienced during this test. The very slight decrease in TKN might reflect accelerated resynthesis at elevated temperatures. Fecal coliform bacteria declined by 98.9%. The VSS reduction rate fell below 3% per day after 16 days detention time.

Batch Test No. 2

Undigested concentrated WAS was used (3.63% TSS) and improvements in sampling and temperature control were instituted to avoid problems encountered during the first batch test.

Experimental data for Batch Test 2 are presented in Tables 17, 18 and 19. Table 17 summarizes data from laboratory analysis, Table 18 presents average operating data and Table 19 indicates the calculated values for TSS and VSS reductions.

Figure 44 is a DO profile taken at fifteen separate locations within the test tank to demonstrate the homogenity and adequate mixing of the biomass undergoing oxygenation.



LOCATION	D.O. (mg/l)	LOCATION	D.O. (mg/l)	LOCATION	D.O. (mg/l)
N-1	0.8	S-1	0.6	M-1	0.55
N-2	0.4	S-2	0.6	M-2	0.55
NE-3	0.4	SW-3	0.6	M-3	0.60
E-1	0.3	W-1	0.7		
E-2	0.5	W-2	0.4		
SE-3	0.4	NW-3	0.5		

Fig. 44. Pure oxygen batch test no. 2 DO profile

Table 17. Pure oxygen digester batch test no. 2 - laboratory data (mg/l unless other units indicated)

DATE	pH Units	CONDUCTIVITY μmho/cm^2	SUSPENDED SOLIDS		DISSOLVED SOLIDS		COD	NITROGEN-N				ALKALINITY as $CaCO_3$	FECAL COLI no./ml
			TSS	VSS	TDS	VDS		PO_4	NO_3	NH_3	TKN		
INITIAL 1/10/73	6.0	570	36,300	30,000	1,200	353	51,500	888	0.14	66	3,070	2,000	6.1×10^7
1/10	6.3	900	33,600	28,700	2,425	1,405							
1/11	6.2	2,500	31,000	26,600	3,410	2,085							
1/12	6.6	2,500	29,300	25,300	3,800	2,455							
1/13	6.9	NA	23,900	19,100	NA	2,790						2,420	
1/14	6.1	1,100	23,200	18,500	3,420	2,000							
1/15	7.4	6,960	24,700	20,100	3,640	2,120							
1/16	7.2	7,200	26,700	23,300	3,250	1,850							
1/17	7.6	6,300	20,200	16,400	3,300	1,870							
1/18	6.3	4,700	19,700	15,800	3,660	1,980							
1/19	6.7	4,850	17,600	15,800	3,650	2,000							
1/20	6.3	4,640	17,800	15,600	3,710	2,140							
1/21	6.4	4,600	19,400	13,300	4,130	2,430						1,220	
1/22	L.A.	L.A.	22,100	16,100	4,110	2,260							
1/23	6.5	4,180	17,300	13,400	4,360	2,740							
1/24 FINAL	6.6	6,250	21,200	15,900	3,970	2,480	24,700	NA	NA	700	2,220	1,400	2.0×10^7

Table 18. Pure oxygen digester batch test no. 2 - field data

DATE	OXYGEN PRESS.(1)		OXYGEN FLOW(2)		OXYGEN TEMP. (°F)(3)	O_2 SUPPLY		D.O. (mg/l)	SLUDGE (3) TEMP. (°F)
	1 & 2	3	1 & 2	3		(scfd)(4)	(lb/day)(5)		
1/10/73	22.6	23.0	1.72	0.35	90.1	2,393	199	3.6	82.1
1/11	20.6	20.5	1.33	0.26	83.9	1,706	142	3.4	91.6
1/12	20.6	20.6	1.30	0.26	68.7	1,706	142	N.A.	93.6
1/13	21.0	21.0	1.21	0.25	72.5	1,555	129	13.4	95.0
1/14	17.2	18.1	0.65	0.18	72.9	787	65	7.3	91.0
1/15	25.2	21.2	0.61	0.23	78.4	989	82	5.2	89.4
1/16	20.4	19.2	0.42	0.21	79.7	659	55	6.2	79.5
1/17	17.3	17.5	0.32	0.20	73.1	493	41	5.4	76.2
1/18	15.9	15.8	0.27	0.18	67.2	400	33	12.6	75.2
1/19	15.2	14.6	0.25	0.18	68.2	371	31	16.7	77.7
1/20	15.0	15.0	0.25	0.16	64.8	352	29	13.8	70.6
1/21	14.9	14.0	0.25	0.16	63.3	345	29	15.1	69.6
1/22	15.1	16.2	0.25	0.15	83.4	362	30	16.7	72.2
1/23	15.9	--	0.25	--	78.4	227	19	15.9	76.5

(1) psig (diffusers 1-2 and 3) x 0.0703 = kg/cm^2

(2) cfm (diffusers 1-2 and 3) x 0.472 = l/sec

(3) (°F-32) 5/9 = °C

(4) scfc x 0.0283 = m^3/day at STP

(5) lb/day x 0.454 = kg/day

Table 19. Pure oxygen digester batch test no. 2 - inventory mass reduction

DATE	LIQUID INVENTORY (lb)(1)	TSS (mg/l)	VSS (mg/l)	SOLIDS INVENTORY		PERCENT MASS REDUCTION	
				TSS (lb) (1)	VSS (lb) (1)	TSS	VSS
INITIAL 1/10/73	14,349	36,300	30,000	520.9	430.5	--	--
1/10 COMP	14,130	33,600	28,700	474.8	405.5	8.9	5.8
1/11	12,227	31,000	26,600	379.0	325.2	27.2	24.4
1/12	12,044	29,300	25,300	352.9	304.7	32.2	29.2
1/13	11,883	23,900	19,100	284.0	227.0	45.5	47.3
1/14	11,692	23,200	18,500	271.2	216.3	47.9	49.8
1/15	11,531	24,700	20,100	284.8	231.8	45.3	46.1
1/16	12,995	26,700	23,300	347.0	302.8	33.4	29.7
1/17	12,922	20,200	16,400	261.0	211.9	49.9	50.8
1/18	12,812	19,700	15,800	252.4	202.4	51.5	53.0
1/19	12,702	17,600	15,800	223.6	200.7	57.1	53.4
1/20	12,629	17,800	15,600	224.8	197.0	56.8	54.2
1/21	12,519	19,400	13,300	242.9	166.5	53.4	61.3
1/22	12,446	22,100	16,100	275.1	200.4	47.2	53.4
1/23	12,373	17,300	13,400	214.0	165.8	58.9	61.5
1/24 FINAL	12,263	21,200	15,900	260.0	195.0	50.1	54.7

(1) lb x 0.454 = kg

An air calibrated DO meter accurate to ± 0.2 mg/l was used for this purpose. The use of a water jacket heat exchanger for the second test kept the sludge temperature below 37.8°C (100°F), the overall average being 26.9°C (81°F).

Excessive foaming was observed during the second day of this test and continued to be a problem for the duration of the test. The foaming caused the loss of solids from the system which lowered the sludge level to the vicinity of the pump suction. The lowered liquid level accentuated the foaming problem even more requiring 623 liters (165 gal) of water to be added on January 16, 1973.

DO Uptake

A YSI model 54 oxygen meter with a model 5420A BOD polarographic probe in a standard 300 ml BOD bottle was used to measure the oxygen respiration rate. The sample was oxygenated prior to analysis by diffusing pure O_2 into the liquid using a carborundum stone diffuser. Measurement of DO decline versus time was taken once per minute until a DO concentration of less than 1.0 mg/l was observed. This method, although satisfactory for dilute WAS (0.5 to 1.0% TSS) was found to be inadequate for the more concentrated sludges (4.0 to 5.0% TS) used in the pure oxygen batch tests. The viscous nature of the polymer conditioned and air flotation thickened sludge caused erratic readings from gaseous oxygen collecting within the sample and on the probe. Therefore no attempt was made to calculate O_2 transfer efficiencies for this test.

Although a relatively high DO was maintained (up to 15.6 mg/l) no difference was observed in the rates of solids digestion that could be related to the DO concentrations. Increasing pH followed by a decline was observed during this test. The difference between initial and final pH values during the second batch test was much less (0.6 pH units) than for the first test (1.3 units). High temperatures were not a factor during the second test. Volatile organic acids losses were therefore less than during the first test. Conductivity increased eleven fold between initial and final samples. VSS were reduced by 53% after 14 days. This percent reduction was also observed after 7 days.

TDS and VDS values increased rapidly during the first four days of the test, with final values on the fourteenth day closely approximating values obtained on the fourth day.

COD was reduced by 52%, correlating well with the VSS reduction previously noted. A very high deamination rate resulted in a more than ten fold increase in NH_4 concentration between initial and final samples. TKN was reduced by 27.7%.

The lab data in Table 17 have not been corrected for evaporation losses. On a total inventory basis, the percent reduction is higher than indicated in this table. Fecal coliform reduction during this test was 67.2%.

Batch Test. No. 3

Diffused air aerobically digested sludge was used in this test. The small VSS reduction observed in this test is attributed to the relatively low initial VSS/TSS ratio. The foaming problem experienced during batch test No. 2 was corrected during this test by the installation of a foam suppression system consisting of a recycle pump and spray nozzles.

Experimental data for Batch Test 3 are presented in Tables 20, 21 and 22. Table 20 summarizes laboratory analyses, Table 21 presents average operating data and Table 22 shows calculations of TSS and VSS reductions.

Because of the relatively low respiration rates and resultant high oxygen concentration that occurred midway through this test, two of the three diffusers installed in the system were removed. The previously mentioned problems with the method of DO uptake measurement were not resolved during this test. Virtually no change was noted between the initial and final pH. The 2.5 fold conductivity increase was less than for previous tests. VSS concentration declined by only 22.2% and the VSS/TSS ratio of the final sample was 2.7% higher (82.6%) than the initial sample (79.9%). TDS increased approximately 3.6 fold.

Ammonium-N in the final sample was 20% higher than the initial sample and the alkalinity declined by 52.2%. From the above data it was apparent that this test was not typical of pure oxygen digestion performance with undigested WAS.

Table 20. Pure oxygen digester batch test no. 3 - laboratory data (mg/l unless other units indicated)

DATE	pH (Units)	COND. µmho/cm^2	SUSPENDED SOLIDS TSS	SUSPENDED SOLIDS VSS	DISSOLVED SOLIDS TDS	DISSOLVED SOLIDS VDS	COD	PO_4	NITROGEN NO_3	NITROGEN NH_4	NITROGEN TKN	ALKALINITY (as $CaCO_3$)	FECAL COLI no./ml
INITIAL	6.4	1440	45700	36500	1610	533	57700	1150	0.26	250	3130	1160	1.3×10^6
1/31/73	6.4	1770	42100	33400	2715	1525							
2/1	6.8	2440	36500	30000	3580	2345							
2/2	7.1	2200	35000	28000	3920	2560							
2/3	6.7	2570	44400	32400	3705	2230							
2/4	6.8	3400	33300	24500	4120	2630							
2/5	6.8	3250	33600	25000	4330	2850							5.0×10^6
2/6	6.8	3390	32300	24900	4480	3040						2480	
2/7	6.3	2520	33900	25200	4700	3010	41300						
2/8	6.8	4500	32200	23700	4600	2720							
2/9	6.2	2690	33900	25800	5200	3020							
2/10	6.2	3430	32300	24400	4820	2620							
2/11	6.1	4380	28400	25100	4940	2630							
2/12	6.0	4020	29300	21600	5590	3140						1640	
2/13	6.2	4430	30700	26200	5510	3050							
2/14	6.5	3760	31200	23500	5180	2940							
2/15	6.4	3500	31900	24800	5120	2920							
2/16	7.2	4600	29900	22500	5290	3010							
2/17	N A	N A	31600	24300	4890	2850							
2/18	7.0	3660	32800	24000	5200	3070							
2/19	6.3	3610	34800	25700	5340	3120							
2/20	5.8	3660	34500	29300	--	--							
FINAL	6.2	3600	34400	28400	5780	3360	N A	N A	N A	300	N A	555	N.A

Table 21. Pure oxygen digester batch test no. 3 - field data

DATE	OXYGEN PRESS.(1)		OXYGEN FLOW(2)		OXYGEN TEMP. (°F)(3)	O_2 SUPPLY		D.O. (mg/l)	SLUDGE TEMP. (°F)(3)
	1 & 2	3	1 & 2	3		(scfm)(4)	(lb/day)(5)		
1/31/73	30.3	29.3	1.34	0.37	70	2,313	192	7.5	72
2/1	25.6	25.8	0.98	0.33	81	1,617	134	0.5	80
2/2	27.5	27.9	1.14	0.33	76	1,894	157	1.4	81
2/3	26.3	25.8	1.01	0.30	73	1,616	134	1.4	82
2/4	26.0	25.2	0.98	0.28	69	1,528	127	2.9	82
2/5	25.2	25.2	0.95	0.27	73	1,466	122	1.7	82
2/6	25.7	25.2	0.96	0.28	66	1,485	123	2.5	76
2/7	22.7	22.7	0.85	0.26	58	1,210	100	3.8	76
2/8	19.6	20.1	0.63	0.23	59	858	71	2.2	76
2/9	16.9	REMOVED*	0.44	REMOVED*	66	376	31	7.7	75
2/10	15.0	--	0.28	--	66	240	20	8.0	75
2/11	14.7	--	0.26	--	67	210	17	12.1	72
2/12	17.0*	--	0.21*	--	65	193	16	7.7	69
2/13	15.0	--	0.16	--	62	137	11	2.8	68
2/14	15.1	--	0.15	--	64	130	11	2.0	68
2/15	15.4	--	0.14	--	58	121	10	2.0	66
2/16	16.5	--	0.14	--	65	127	10	1.2	64
2/17	16.2	--	0.14	--	62	125	10	1.4	64
2/18	16.5	--	0.14	--	65	127	10	1.1	66
2/19	18.5	--	0.17	--	60	163	13	1.6	64
2/20	20.0	--	0.20	--	59	202	17	5.5	63

*REMOVED NO. 3 DIFFUSER ON 2/9 AND NO. 1 DIFFUSER ON 2/12.

(1) psig (diffusers 1-2 and 3) x 0.0703 = kg/cm^2
(2) cfm (diffusers 1-2 and 3) x 0.472 = l/sec
(3) (°F-32) 5/9 = °C
(4) scfd x 0.0283 = m^3/day at STP
(5) lb/day x 0.454 = kg/day

Table 22. Pure oxygen digester batch test no. 3 - inventory mass reduction

DATE	LIQUID INVENTORY (lb) (1)	TSS (mg/l)	VSS (mg/l)	SOLIDS INVENTORY TSS (lb)(1)	SOLIDS INVENTORY VSS (lb)(1)	PERCENT MASS REDUCTION TSS	PERCENT MASS REDUCTION VSS
INITIAL 1/31/73	14386	45700	36500	657.4	525.1		
1/31/73 COMP.	14284	42100	33400	601.4	477.1	8.5	9.1
2/1	14166	36500	30000	517.1	425.0	21.3	19.1
2/2	14049	35000	28000	491.7	393.4	25.2	25.1
2/3	13932	44400	32400	618.6	451.4	5.9	14.0
2/4	13830	33300	24500	460.5	338.8	29.9	35.5
2/5	13727	33600	25000	461.2	343.2	29.8	34.6
2/6	13610	32300	24900	439.6	338.9	33.1	35.4
2/7	13508	33900	25200	457.9	340.4	30.3	35.2
2/8	13391	32200	23700	431.2	317.4	34.4	39.5
2/9	13288	33900	25800	450.5	342.8	31.5	34.7
2/10	13171	32300	24400	425.4	321.4	35.3	38.8
2/11	13054	28400	25100	370.7	327.6	43.6	37.6
2/12	12951	29300	21600	379.5	279.7	42.3	46.7
2/13	12834	30700	26200	394.0	336.2	40.1	36.0
2/14	12732	31200	23500	397.2	299.2	39.6	43.0
2/15	12615	31900	24800	402.4	312.8	38.8	40.4
2/16	12512	29900	22500	374.1	281.5	43.1	46.4
2/17	12410	31600	24300	392.1	301.6	40.3	42.6
2/18	12293	32800	24000	403.2	295.0	38.7	43.8
2/19	12175	34800	25700	423.7	312.9	35.5	40.4
2/20	12073	34500	29300	416.5	353.7	36.6	32.6
2/21/73 FINAL	11970	34400	28400	411.8	339.9	37.4	35.3

(1) lb x 0.454 = kg

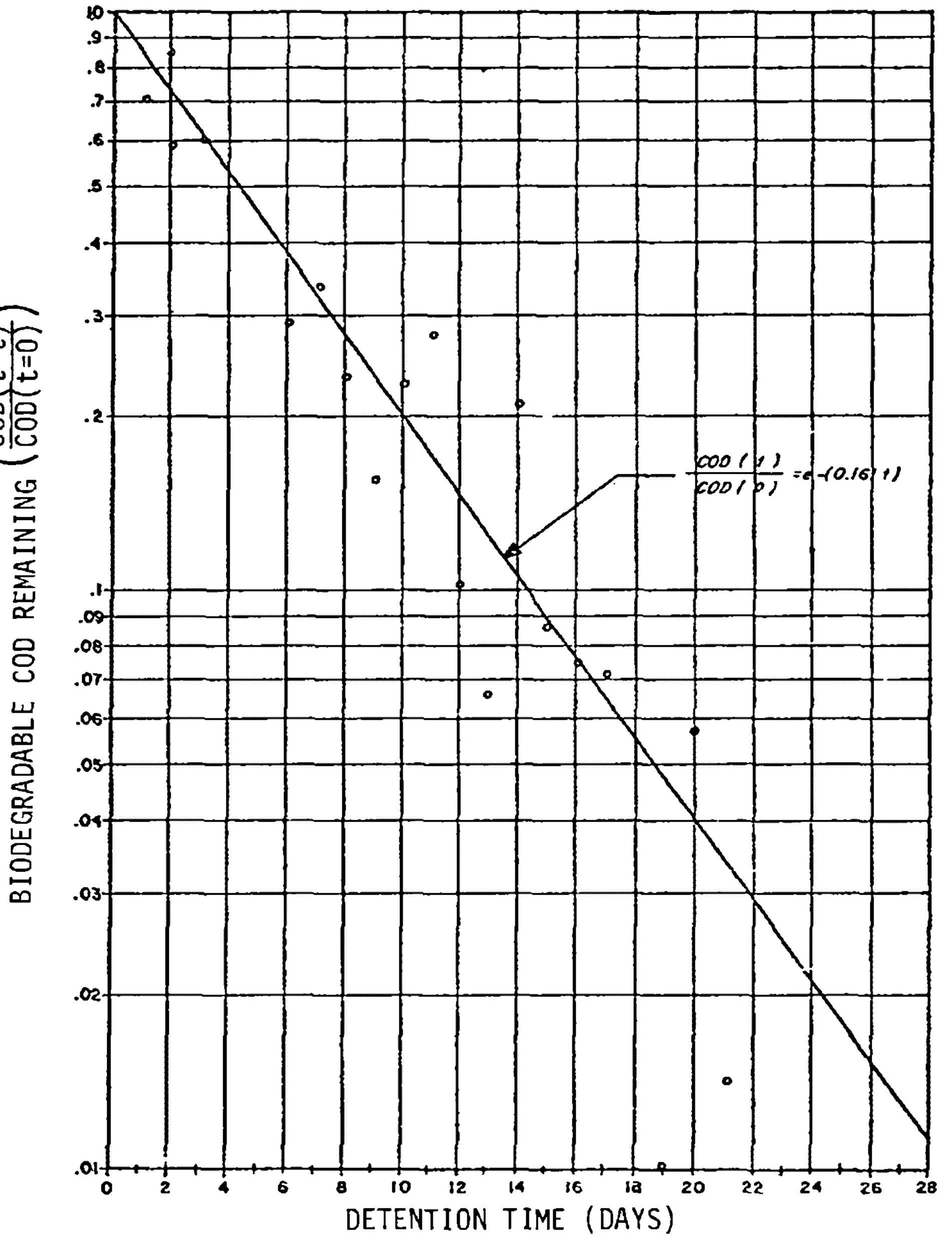


Fig. 45. Pure oxygen batch test no. 4 biodegradable COD reduction versus detention time

Table 23. Pure oxygen digester batch test no. 4 - laboratory data (mg/l unless other units indicated)

DATE	SUSPENDED SOLIDS		DISSOLVED SOLIDS		COND. $\mu mho/cm^2$	pH Units	ALK.	COD	NO_3	NH_4	TKN	PO_4
	TSS	VSS	TDS	VDS								
INITIAL	38300	32900	2080	585	1610	6.4		60800	.22	495	2900	748
3/8/73	34600	28300	2110	745	1970	6.3	1020	50500				
3/9	35800	31500	3500	1830	2550	6.6		46400				
3/10	33800	27100	3940	2320	2800	6.8		46900				
3/11	31200	24900	5800	3700	2850	7.0	2140	NA				
3/12	30000	24100	NA	NA	NA	NA	NA	NA				
3/13	28800	23500	4600	1900	3470	7.3		36100				
3/14	30200	24900	2800	100	3700	7.5	2340	37600				
3/15	28400	23600	3400	500	4520	6.8		34200				
3/16	29200	22400	2800	1300	4320	7.0		31600				
3/17	25000	20900	3940	2420	4180	7.0		33900				
3/18	22800	18600	8100	4200	3910	6.3		35700				
3/19	21000	16600	9700	6000	3890	6.2	1520	29600				
3/20	26800	21600	3400	440	3780	6.7		28300				
3/21	25500	18700	4300	3100	3930	6.8		33300				
3/22	31700	24600	4260	2560	2890	6.9		29000				
3/23	27100	22700	4460	2580	3450	6.7		28600				
3/24	27200	20800	4460	2600	3370	6.7		28500				
3/25	29500	22000	4220	2380	2920	6.4		29700				
3/26	28200	23800	4060	2050	2800	6.7	1095	26100				
3/27	29200	26400	4180	2200	2870	6.2		28000				
3/28 FINAL	27000	22800	4070	2130	NA	NA	713	26500	712	90	2020	1120

Table 24. Pure oxygen digester batch test no. 4 - field and inventory mass reduction data

DATE	D.O. mg/l	SLUDGE TEMP. (°F)(1)	LIQUID INVENTORY (lb)(2)	TSS (mg/l)	VSS (mg/l)	SOLIDS INVENTORY TSS (lb)(2)	SOLIDS INVENTORY VSS (lb)(2)	PERCENT MASS REDUCTION TSS	PERCENT MASS REDUCTION VSS
INITIAL	1.6	66	14385.9	38300	32900	551.0	473.3	--	--
3/8/73	1.6	66	14312.7	34600	28300	495.2	405.0	10.1	14.4
3/9	1.8	74	14224.9	35800	31500	509.2	448.1	7.6	5.3
3/10	1.6	77	14093.1	33800	27100	476.3	381.9	13.5	19.3
3/11	2.1	77	13888.1	31200	24900	433.3	345.8	21.4	26.9
3/12	2.4	79	14166.3	30000	24100	424.9	341.4	22.9	27.9
3/13	2.5	80	14371.3	28800	23500	413.9	337.7	24.9	28.6
3/14	2.8	81	14385.9	30200	24900	434.4	358.2	21.2	24.3
3/15	2.2	82	14415.2	28400	23600	409.4	340.2	25.7	28.1
3/16	2.3	83	14444.5	29200	22400	421.8	323.6	23.4	31.6
3/17	4.0	81	14371.3	25000	20900	359.3	300.4	34.8	36.5
3/18	8.7	76	14166.3	22800	18600	323.0	263.5	41.4	44.3
3/19	N.A.	72	14342.0	21000	16600	301.2	238.1	45.3	49.7
3/20	5.7	74	14349.3	26800	21600	384.6	309.9	30.2	34.5
3/21	1.6	76	14385.9	25500	18700	366.8	269.0	33.4	43.2
3/22	1.1	76	14517.7	31700	24600	460.2	357.1	16.5	24.5
3/23	0.8	79	14458.1	27100	22700	391.8	328.2	28.9	30.7
3/24	0.8	76	14312.7	27200	20800	389.3	297.7	29.3	37.1
3/25	0.5	73	14137.0	29500	22000	417.0	311.0	24.3	34.3
3/26	1.7	70	14224.9	28200	23800	401.1	338.5	27.2	28.5
3/27	4.7	70	14400.5	29200	26400	420.5	380.2	23.7	19.7
3/28 FINAL	10.7	70	14422.5	27000	22800	389.4	328.8	29.3	30.5

(1) (°F-32) 5/9 = °C

(2) lb x 0.454 = kg

Table 25. Pure oxygen digester batch test no. 5 - laboratory data (mg/l unless other units indicated)

DATE	SUSPENDED SOLIDS		DISSOLVED SOLIDS		COND.	pH	ALK. as	COD	NITROGEN-N			PO4
	TSS	VSS	TDS	VDS	μmho/cm^2	Units	$CaCO_3$		NO_3	NH_4	TKN	
INITIAL	35600	29500	1560	605	1760	7.3	1167	44500	.46	12	2580	716
4/5/73	33300	26100	2480	1200	2560	6.9	1398	40400				
4/6	34500	27300	3110	1770	2420	6.6		37000				
4/7	27700	21700	3590	2290	2570	6.8		33800				
4/8	25100	20600	3290	1960	2740	7.4	1525	34000				
4/9	27300	21200	3550	2210	3600	7.3		30000				
4/10	23400	18400	3080	1640	3100	7.0		26500				
4/11	25000	18500	2840	1440	2570	6.6		27900				
4/12	22400	17900	2490	1200	2440	6.8	1254	27000				
4/13	19400	18400	2700	1060	2270	6.9		24800				
4/14	20100	15600	3000	1240	2430	5.9		25200				
4/15	22200	15200	3020	1340	2390	6.6	599	23300				
4/16	22100	16700	3240	1430	2550	6.0		24800				
4/17	23500	16400	3190	1400	2760	6.0		20280				
4/18 FINAL	22300	16600	3300	1460	2640	5.9	435	20580	148	104	1560	660.8

Table 26. Pure oxygen digester batch test no. 5. - field data

DATE	OXYGEN FLOW (cfm)(1)	OXYGEN PRESSURE (psig)(2)	OXYGEN TEMP. (°F)(3)	OXYGEN SUPPLY (scfd)(4)	OXYGEN SUPPLY lb/day(5)	DO (mg/l)	DO UPTAKE R_r	DO UPTAKE K_r	SLUDGE TEMP. (°F)(3)	O_2 RESPIRED (lb/day)(5)	PERCENT OXYGEN TRANSFER EFFICIENCY
4/5/73	0.53	30	67	742.7	61.6	1.0	156	6.0	73	53.8	87.3
4/6	0.51	30	71	712.0	59.1	1.0	173	6.3	82	59.7	101.0
4/7	0.44	28	61	605.2	50.2	5.2	111	5.1	85	38.3	76.3
4/8	0.33	26	55	445.0	36.9	2.0	82	4.0	82	28.3	76.7
4/9	0.32	27	56	436.7	36.2	1.0	94	4.4	81	32.4	89.5
4/10	0.32	27	68	431.8	35.8	1.2	114	6.2	85	39.3	109.8
4/11	0.30	27	73	402.9	33.4	0.8	88	4.8	85	30.4	88.4
4/12	0.29	27	59	394.7	32.8	1.3	118	6.6	83	40.7	124.1
4/13	0.29	27	69	390.9	32.4	2.3	90	4.9	79	31.1	96.0
4/14	0.25	22	69	314.7	26.1	15.2	57	3.7	73	19.7	5.0
4/15	0.22	18	68	260.4	21.6	11.9	12	0.8	73	4.1	--
4/16	0.21	16	70	239.7	19.9	17.9	21	1.3	72	7.2	--
4/17	0.17	15	62	192.0	15.9	18.0	19	1.2	71	6.6	--
4/18	0.21	15.5	68	79.3	6.6	18.8	12	0.7	70	4.1	--

(1) cfm x 0.472 = l/sec

(2) psig x 0.0703 = kg/cm^2

(3) (°F-32) 5/9 = °C

(4) lb/day x 0.454 = kg/day

(5) scfd x 0.0283 = m^3/day at STP

Table 27. Pure oxygen digester batch test no. 5 - inventory mass reduction

DATE	LIQUID INVENTORY (lb)(1)	TSS (mg/l)	VSS (mg/l)	SOLIDS INVENTORY TSS (lb)(1)	SOLIDS INVENTORY VSS (lb)(1)	PERCENT MASS REDUCTION TSS	PERCENT MASS REDUCTION VSS
INITIAL	14349.3	35600	29500	510.8	423.3		
4/5/73	14298.1	33300	26100	476.1	373.2	6.8	11.8
4/6	14283.4	34500	27300	492.8	389.9	3.5	7.9
4/7	14283.4	27700	21700	395.6	309.9	22.5	26.8
4/8	14254.1	25100	20600	357.8	293.6	29.9	30.6
4/9	14400.5	27300	21200	393.1	305.3	23.0	27.9
4/10	14371.3	23400	18400	336.3	264.4	34.2	37.5
4/11	14298.1	25000	18500	357.4	264.5	31.2	37.5
4/12	14371.3	22400	17900	321.9	257.2	37.0	39.2
4/13	14254.1	19400	18400	276.5	262.3	45.9	38.0
4/14	14283.4	20100	15600	287.1	222.8	43.8	47.4
4/15	14166.3	22200	15200	314.5	215.3	38.4	49.1
4/16	14283.4	22100	16700	315.7	238.5	38.2	43.6
4/17	14371.3	23500	16400	337.7	235.7	33.9	44.3
4/18 FINAL	14349.3	22300	16600	320.0	238.2	37.3	43.7

(1) lb x 0.454 = kg

Batch Test No. 4

Undigested WAS (3.83% TSS) was used in this test. In order to compensate for evaporation losses during the test period, make up water was added daily to maintain the initial volume of 6500 liters (1722 gal). Because of the wide fluctuations in solids data previously noted, the biomass was analyzed daily for COD.

Experimental data for Batch Test 4 are presented in Tables 23 and 24. Table 23 summarizes laboratory analyses and Table 24 presents operating data and calculations of TSS and VSS reductions.

Oxygen uptake calculations were not listed in these tables because of continuing difficulty in measurement.

Figure 45 shows the reduction of biodegradable COD during the 21 day test period. Biodegradable COD was defined as that fraction of the total COD reduced by the end of each test. The biodegradable COD reduction rate coefficient was equal to 0.161 (16.1% per day).

TSS and VSS concentrations were reduced by 29.5 and 30.7% respectively. TDS and VDS increased by 95.7 and 264.1% respectively. COD reduction between the initial and final sample was 56.4%. The pH reduction was minimal (0.2 units) while alkalinity was reduced by 30%. TKN was reduced by 30.3%, ammonium-N was reduced by 81.8% and nitrates increased over 3000 fold to 712 mg/l in the final sample.

Bath Test No. 5

Mechanical and operational problems encountered in the previous batch tests were solved prior to start of this test. The data from this test were considered to be more representative of open tank aerobic digestion than data from the previous batch tests and will be referred to as the standard for pure oxygen batch test performance.

Experimental data for Batch Test 5 are presented in tables 25, 26 and 27. Table 25 summarizes laboratory analyses, Table 26 presents average operating data and Table 27 shows calculations of TSS and VSS reductions.

The oxygen uptake rate method was improved by injecting hydrogen peroxide (3% solution) into the biomass within the 500 ml respiration chamber at a controlled application rate to provide the oxygen source for respiration. Homogeneous mixing was accomplished by a two propeller mixer operating at 700 rpm. A YSI dissolved oxygen probe mounted on top of the respiration chamber transmitted a signal through the DO meter to a strip chart recorder. The oxygen uptake rate was calculated from the constant slope section of the chart recording. The optimal mixing speed and the hydrogen peroxide injection rate were determined by trial and error to avoid toxic peroxide effects. Reliability of this method within $\pm$ 10% was verified by testing several aliquots of the same sample for reproducibility. Less than 5 minutes elapsed between sample collection and analysis to prevent biomass anoxia.

Figure 46 shows the relationship of specific oxygen uptake K_r to detention time. During the first nine days, K_r varied between 4 and 6 mg/hr/g VSS. This data appears to substantiate the previous observations concerning cyclical digestion and re-synthesis. On the tenth day, K_r dropped to less than 1.0 mg/hr/g VSS. It is suggested that for batch aerobic digestion, a K_r of less than 3.0 can be used to define satisfactory stabilization.

During the first 9 days of this test, K_r averaged 5.4, DO concentration averaged 1.7 mg/l and oxygen transfer efficiency averaged 93.7%. During the last 4 days of the test, when K_r averaged 1.0, DO concentration rose to an average of 16.2 mg/l with a consequent reduction in oxygen transfer efficiency. In order to ensure a consistently high oxygen transfer efficiency in an open tank system, the DO must be controlled below the air-liquid saturation limit of 7.0 mg/l at 20^{o}C and Denver altitude.

TSS and VSS reductions averaged 37.4% and 43.7% respectively, while TDS and VDS increased by 212% and 241.3% respectively. Conductivity increased 50%, COD declined 53.8% and pH declined by 1.4 units from 7.3 to 5.9 in the final sample. This decline in pH was accompanied by a 62.7% decrease in alkalinity and a three hundred fold increase in nitrate concentration to 248 mg/l. Ammonium-N increased 8.7 fold while TKN declined 39.5%.

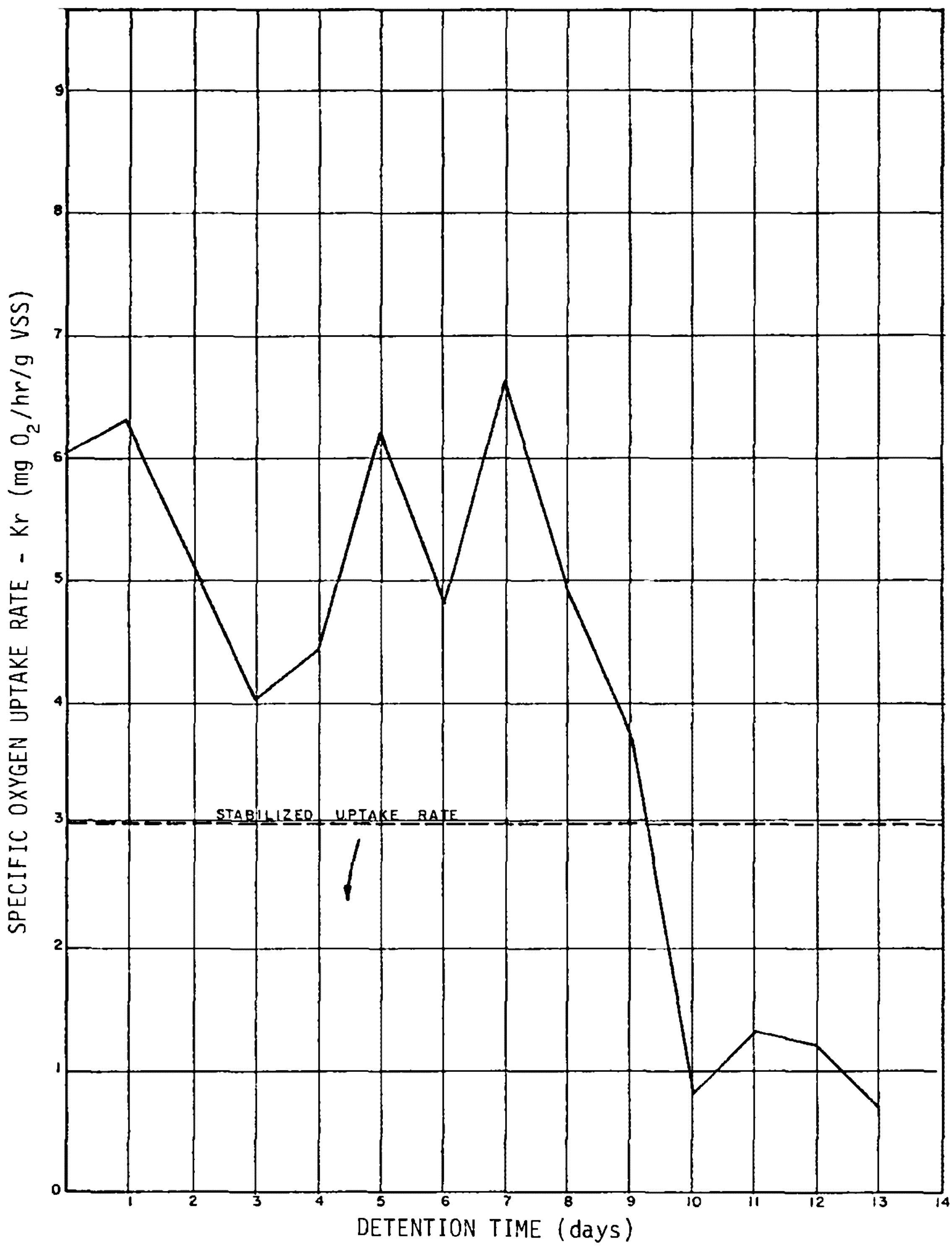


Fig. 46. Pure oxygen batch test no. 5 specific oxygen uptake rate versus detention time

Summary of Pure Oxygen Batch Test Results

The five pure oxygen batch tests indicated that the biodegradable VSS reduction rate levels off after approximately 15 days. Figure 47 shows that by the fifteenth day all 5 tests had reached a 5%/day VSS reduction rate, compared with initial rates of 15 to 25%/day. Biodegradable VSS was defined as that fraction of the total VSS reduced by the end of each test. The final sample did not always have the lowest VSS concentration. Although triplicate analysis of TSS and VSS were done to reduce the possibility of error, sampling procedure may account in part for this variability. The repeatability of the cyclical solids concentration phenomenon in all of the batch tests suggest that alternating periods of digestion and resynthesis by heterotrophic and autotrophic organisms may be involved.

The rate of endogenous respiration of biodegradable VSS is represented by the first order reaction equation:

$$\frac{dS}{dt} = -kS$$

where

k = rate of decay constant (aerobic digestion rate coefficient)

S = concentration of biodegradable cell material at any time

t = detention time (days)

Integration of the above equation gives:

$$\ln\left[\frac{S(t=t)}{S(t=0)}\right] = -kt$$

If the system follows first order kinetics, the plot on semi-logarithmic paper of the ratio of the biodegradable VSS at any time (t) to the VSS at time zero versus detention time will yield a straight line.

Table 28 summarizes the mass reduction data for all of the batch tests including values for aerobic digestion rate coefficients on a VSS and COD basis: Batch test No. 3 was unique in that a previously air digested material was used as the starting sludge

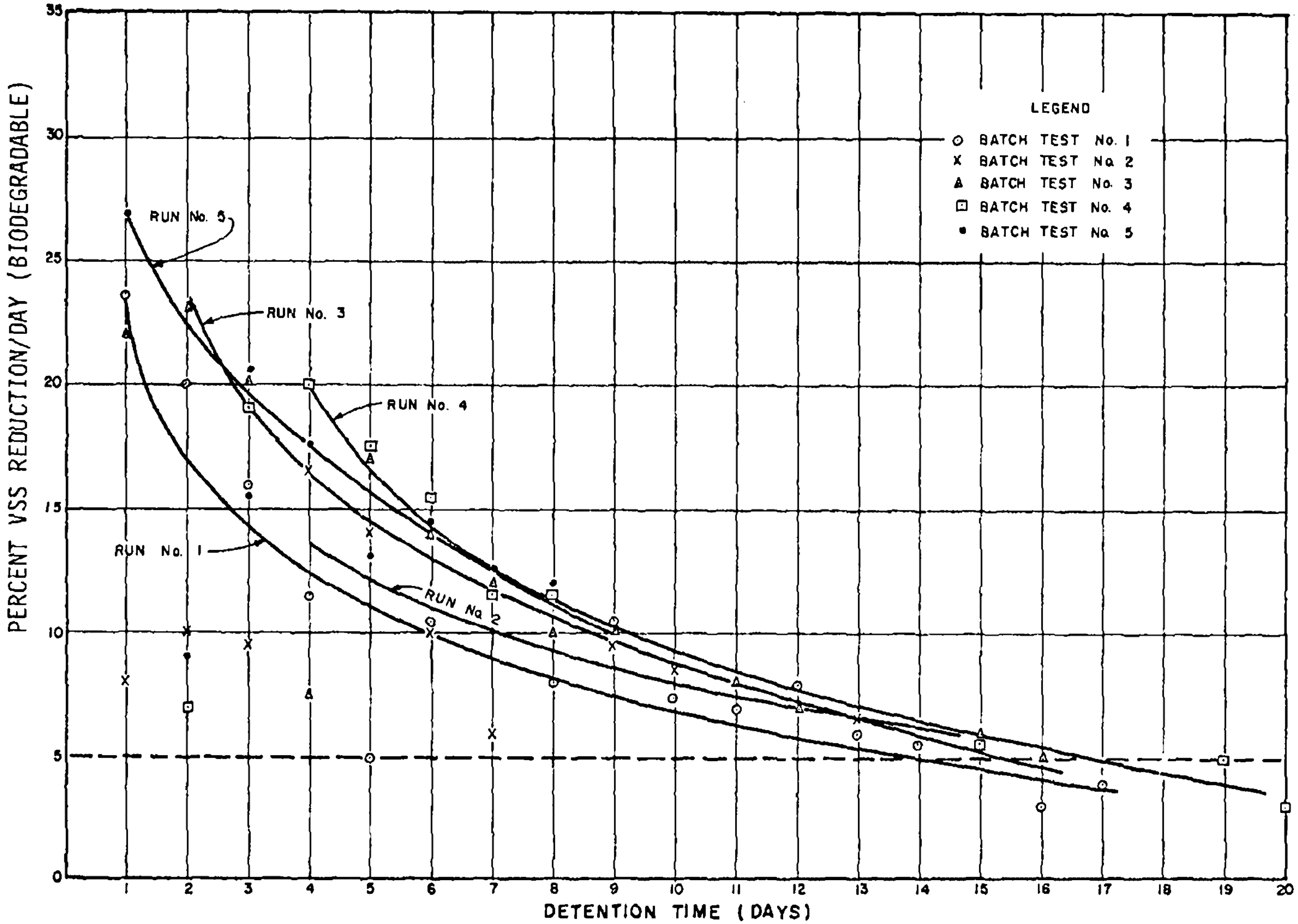


Fig. 47. Pure oxygen batch tests biodegradable VSS reduction versus detention time

Table 28. Pure oxygen digester batch tests 1-5 - biomass reduction summary

SAMPLE	BATCH TEST NO.	DETENTION TIME DAYS	VSS/TSS RATIO initial	VSS/TSS RATIO final	VSS/TSS RATIO Δ %	PERCENT VSS REDUCED*	BIODEGRADABLE AEROBIC DIGESTION RATE COEFFICIENT k_{VSS}	BIODEGRADABLE AEROBIC DIGESTION RATE COEFFICIENT k_{COD}
W A S UNDIGESTED	1	21	0.865	0.844	-2.1	53.7	0.143	-
W A S UNDIGESTED	2	15	0.826	0.750	-7.6	54.7	0.175	-
W A S UNDIGESTED	4	21	0.859	0.844	-1.5	30.5	0.204	0.174
W A S UNDIGESTED	5	14	0.829	0.744	-8.5	43.7	0.273	0.190
AVG (UNDIGESTED)			0.845	0.796	-5.0	45.7	0.200	0.182
W A S AIR DIGESTED	3	21	0.799	0.826	+2.7	35.3	0.182	-

* Based on initial versus final VSS concentration.

for the test. Tests 1, 2, 4 and 5 were loaded with previously undigested WAS.

VSS/TSS ratio was higher for the undigested sludge (84.5%) than it was for the air digested WAS (79.9%). The final VSS/TSS ratio for tests 1, 2, 4 and 5 averaged 79.6% for test 3. The average of the four tests using undigested material showed a net reduction of 5% in the VSS/TSS ratio.

The percent VSS reduced based on the difference between the initial and final sample averaged 45.7% for tests 1, 2, 4 and 5 compared with 35.3% for test 3. The VSS remaining plotted against detention time showed an aerobic digestion rate coefficient of 0.071 with a coefficient of correlation of -0.920 for batch test 5.

A comparison of digestion rates in batch test 5 compared with batch test 3 appears in Figure 48. The biodegradable VSS reduction rate was 50% higher in batch test 5. The reduction rate coefficient was lower on a COD basis than on a VSS basis in batch test 5. The most efficient utilization of pure oxygen for aerobic digestion was obtained by using an undigested WAS with a high initial VSS/TSS ratio.

Comparison of Metro Denver and Batavia Pure Oxygen Batch Tests

One study on aerobic digestion reported in the literature where pure oxygen was used appears in E.P.A. report No. 17050DNW02/72.[12] The aerobic digestion experiments in this study at Batavia, New York were performed entirely on an oxygen WAS with low VSS/TSS ratios (67.6% - 74.1%). Figure 49 compares results for runs 6 and 8 at Batavia with batch test 5 results of this study. The biodegradable VSS digestion rate coefficient in the Batavia study was 0.12 compared to 0.27 in the Metro Denver batch test 5. The coefficient of correlation for the Batavia and Metro Denver tests are both significant at the 95% confidence level. For SRT of 6 days, 20% of the biodegradable VSS remained in the Metro Denver batch system compared with 48% remaining in the Batavia system.

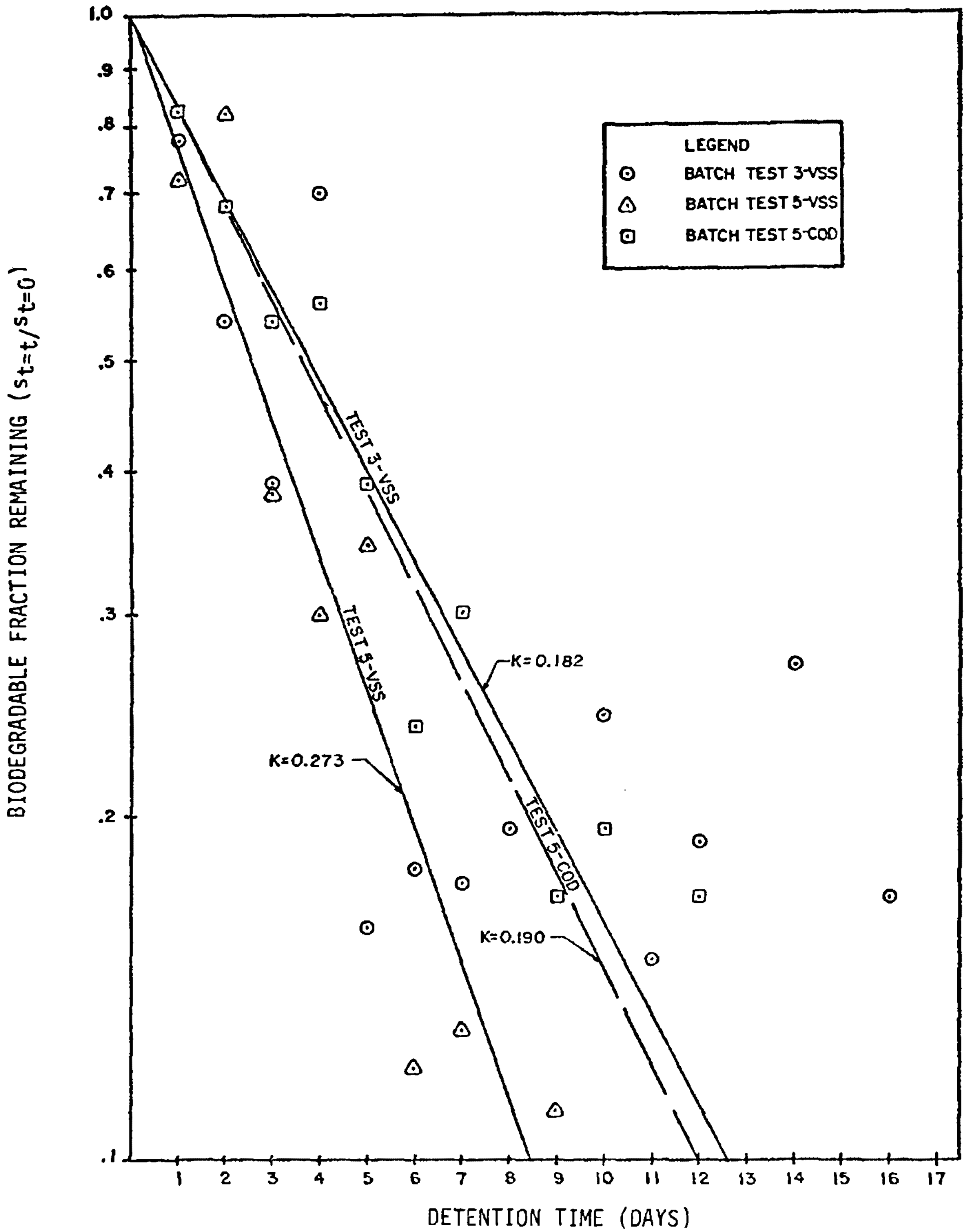


Fig. 48. Pure oxygen batch test 3 and 5 biodegradable COD and VSS reductions versus detention time

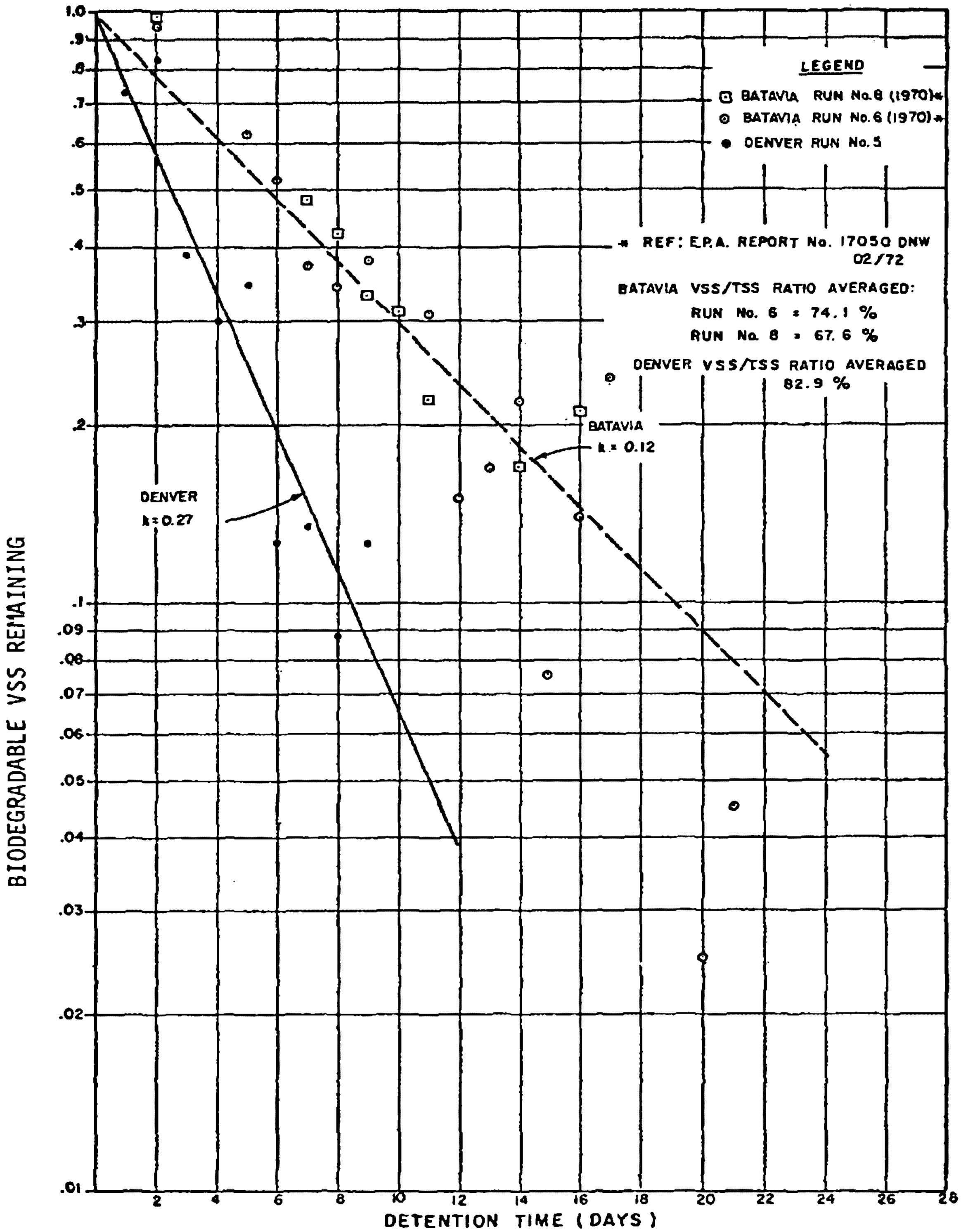


Fig. 49. Comparison of Batavia and Denver pure oxygen batch test VSS reduction versus detention time

Oxygen Uptake Rate

If all of the data are included, a rather poor linear relationship is found to exist between oxygen uptake rates (OUR) and biodegradable VSS or total VSS in both the Batavia and Metro systems. Figure 50 however, shows an excellent correlation +0.99 between biodegradable VSS having a concentration greater than 2,000 mg/l and OUR for the Metro data. The endogenous respiration, therefore, must be proportional to the active mass rather than the TSS. Below an active VSS of 2,000 mg/l, changing metabolic states make this level of activity non-linear. In this study, the equation for OUR for solids concentrated above 2,000 mg/l was found to be OUR = 0.0127·VSS (biodegradable) + 39.7, with a correlation coefficient of +0.99. On a biodegradable COD basis the equation was found to be OUR = 0.0066 COD + 35.6, with a correlation coefficient of +0.766. The poor linear relationship that was found initially to exist in the Batavia study also became a very significant relationship when the biodegradable VSS above 2,000 mg/l were substituted for the total VSS.

The results of the pure oxygen batch test portion of this study yielded the following conclusions:

1. A stabilized sludge and 40 to 50% VSS reduction was obtained after one to three weeks of detention time. These values are similar to diffused air digestion rates under ideal laboratory conditions, and are significantly higher than the VSS reduction rates in the Batavia study.

2. The batch test 5 rate coefficient for total VSS reduction was 0.071 compared with 0.038 in the Batavia study. The difference in rates may be due to CO_2 stripping as well as a more effective oxygen-sludge contacting system in the Metro Denver digester.

3. No correlation was observed during any of the tests between DO concentration and VSS digestion rates. The highest DO concentrations occurred when the OUR was at a minimum and the VSS digestion rate was at its lowest. It appeared that above the minimal concentration required to sustain aerobic metabolism, DO concentrations are a result rather than a cause of aerobic digestion reaction rates.

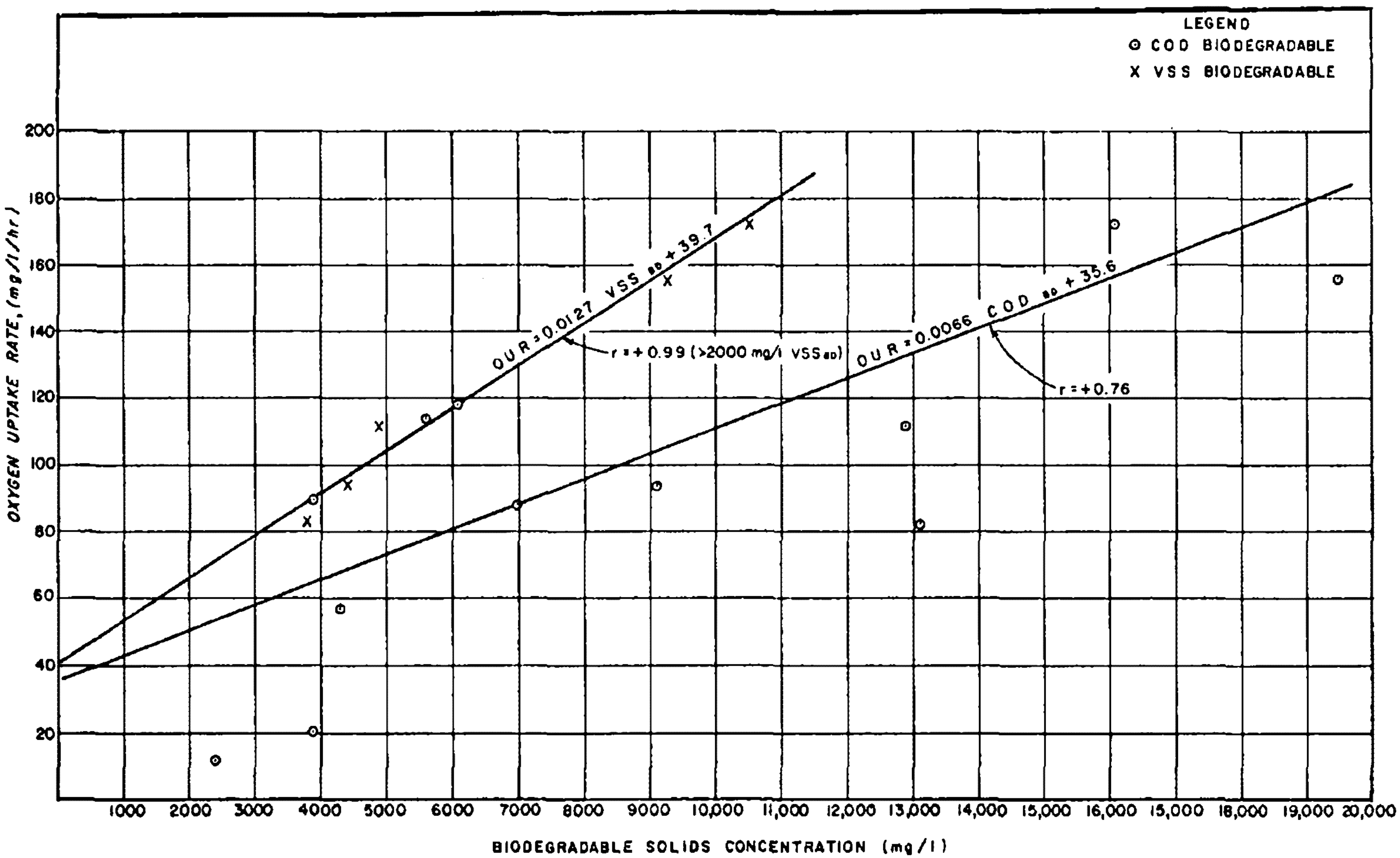


Fig. 50. Pure oxygen batch test no. 5 oxygen uptake rate as a function of biodegradable solids concentration

4. A high degree of oxygen utilization (approximately 92%) was demonstrated in batch test No. 5.

5. The rate of decline in the VSS/TSS ratio in the batch test can be correlated with the percent volatiles of the initial sample. The variations in VSS/TSS ratios during the various batch tests may be explained by the cyclical periodicity of alternate digestion followed by resynthesis of biomass using previously solubilized nutrients (cryptic growth).

6. Microscopic analysis of invertebrate populations revealed that the high concentration of suspended solids results in a stressful "crowding" situation that was inimical to successful growth and reproduction of these organisms in the batch test digester. The addition of cationic high molecular weight polymers to the sludge during dissolved air flotation might also adversely affect the ecological diversity of this system (quaternary ammonium compound polymers have been shown to exert a biostatic effect on numerous microorganisms). At the end of batch test No. 1, only one of the commonly observed invertebrate groups (micro-flagellates) was observed in a viable condition, while no motile invertebrate organisms were observed at the end of batch test No. 2.

   In the pure oxygen batch tests mass decay and endogenous respiration were accomplished almost entirely by bacteria rather than higher invertebrate organisms that were prevalent in the diffused air digestion system under optimal conditions.

Several possible reasons were advanced to explain the relative differences in performance between the aerobic digestion oxygen studies at Batavia and this study. These hypotheses included mixing energy, initial volatile solids concentration, and the different methods of transferring oxygen from the gaseous to the liquid phase. Another possible theory considered the carbon dioxide/ph differences between the initial and final samples. A masters thesis by Thomas J. Weston[13] concluded that "the oxygen unit achieved lower solids reduction and exhibited lower oxygen uptake rates than the air unit." Weston mentioned that in his closed tank system, oxygen digested sludges had significantly lower pH value (4.9), and concluded that pH toxicity may have affected the biological activity of the system thus inhibiting solids reduction. The average volatile solids reduction in Weston's pure oxygen digester was only 23.7% for ten days detention time compared with 41.3% in the air digester for an equivalent detention time. The unique nature of the Marox open tank diffuser system used at Metro allowed for purging of carbon dioxide and volatile organic acids. Thus the final pH was more alkaline than in the Batavia study. The continuous recycling of the liquid sludge through the Metro diffuser to create minute gas bubbles not only aided in purging CO_2 from the system, but also contributed a high degree of mixing energy which could also be related to the degree of volatile solids reduction.

Dissolved oxygen levels were substantially higher in the Batavia experiments and yet the digestion rate coefficient was higher in the Metro Denver experiment suggesting that the effectiveness of oxygen transfer was not a major factor affecting digestion performance.

In summary, a comparison of the relative performance of pure oxygen versus diffused air digestion involves a multiplicity of factors. Only when all of the important factors and their interrelationships are identified can one predict which system will provide the most effective treatment.

EXPERIMENTAL RESULTS - PURE OXYGEN FLOW-THROUGH (FAD) TESTS

Operational Limitations

On the basis of stage one batch test data which indicated that satisfactory stabilization was achieved between 1 and 3 weeks detention time, the second stage flow-through tests were designed to investigate detention times in this range. The commencement of the flow-through tests was delayed, however, due to the May 6, 1973 flood of the South Platte River. This caused an abnormal decline in the VSS/TSS ratio of the Metro WAS from 85% to less than 60%. This effect was noted for several months after the flood's subsidence.

At the start of the second stage phase one testing on June 11, 1973, the VSS/TSS ratio was 77.4%. The second phase starting July 14 through August 22, 1973 had essentially the same VSS/TSS ratio. With commencement of phase three testing on October 20, 1973, the VSS/TSS ratio reached the previously normal levels of 82.5%. During phases four and five from November 1973 through January 1974 the VSS/TSS ratio was 83.5%. The effluent waste solids leaving the pilot plant had an abnormally low TSS/VSS ratio during the first two phases (67.1 - 68.9%). In this respect, these two phases were deemed non-typical.

The major objective of the second stage testing was to determine the breakdown loading rate to the system. The first three phases were designed to duplicate the loading range that had been applied to the diffused air system 1.34 to 3.14 kg VSS/m^3/day (0.83 to 0.196 lb VSS/ft^3/day). The last two phases of this test investigated the performance at much higher loading rates 5.22 to 6.93 kg VSS/m^3/day (0.326 to 0.433 lb VSS/ft^3/day).

During phase one numerous diffuculties were experienced with the sludge recirculation pumps. After conversion of the pilot plant from batch to flow-through, the drive and screw mechanisms of the Moyno pumps failed. Since spare parts were not available, it was decided to use a diaphragm type pump. After start up of the diaphragm pumps several malfunctions occurred requiring shut down of these pumps as well. In order to keep the pilot plant running, two self priming centrifugal pumps were installed. The flow and pressure from these pumps was insufficient to create the requisite gas bubble size. Entrained gases also caused pump cavitation. For this reason the pilot plant was shut down on August 22, 1973. Two new Moyno pumps were utilized in October 1973 and performed satisfactorily during phases 3, 4 and 5 of the second stage testing. The problems with recirculating pumps resulted in DO sag at times during phases one and two due to an inability to create the requisite bubble size.

Concentrated WAS from the air flotation unit was available only during 5 days of the week for phase one of this stage as the process was shut down on weekends. In order to avoid a situation of alternate starve and over-feed, it was decided on July 7, 1973 to save sufficient concentrated WAS over the weekend to enable continuous loading of the pilot plant 7 days a week. No detrimental effects were noted from the loading of slightly septic sludge on weekends, other than an increase in oxygen uptake rates. In October 1973, the air flotation process was converted to a 7 day per week operation, obviating the need to save sludge during weekends.

Measurement of oxygen transfer efficiency was difficult during the initial study phases because of foaming, pump maintenance and our measurement problems. Because of difficulties in DO sensor membrane coating in the concentrated sludge, automatic DO control was not feasible requiring manual control. DO concentrations were determined every 2 hours with a YSI probe. DO concentrations above 7 mg/l occurred on occasion resulting in loss of oxygen to the atmosphere and reduced oxygen transfer efficiency. Prior to phase three, a valving system was installed to allow for flow reversal to the FAD and release any material bridging the slot from the inside. Although the back flush cleaning method did reduce slot bridging, it was not a complete solution to the problem. Even though the influent sludge was processed through a 3 mm screen, much fibrous, pulpy material remained. The ultimate solution to this problem was found to be the substitution of the RAD for the FAD.

Oxygen transfer efficiencies were calculated using average daily OUR based upon two grab samples taken during the morning and afternoon shifts. These values were used to calculate a 24 hour theoretical oxygen demand. The average of twelve oxygen flow and pressure readings per day were used to calculate the daily oxygen supply. A comparison of the oxygen respired per day based on the calculated average OUR with the daily oxygen supply provided a daily O_2 transfer efficiency.

The accuracy of the oxygen flow and pressure measurement varied by less than $\pm$ 5%. Diurnal fluctuations in oxygen respiration rates were significantly greater than oxygen supply variations. This variability led to inaccuracies in calculated oxygen transfer efficiencies, particularly in phases one and two.

Field Data

A summary of field data for the five phases of the FAD test program is included in Table 29. Figure 51 shows the increasing temperature differential between the air temperature and the biomass temperature with increasing loadings. At the lowest loading rate 1.34 kg VSS/m^3/day (.083 lb VSS/ft^3/day) there was virtually no difference between air and biomass temperatures. At the highest loading rate 6.93 kg VSS/m^3/day (0.433 lb VSS/ft^3/day) the temperature differential increased to 20^oC (i.e. ambient temperature averaged 8.4^oC while the biomass in tank B averaged 28.6^oC).

Hydraulic balance through the system took into consideration liquid volume fed, wasted, spilled and/or evaporated. The average for the entire 159 day period showed 2.1% losses as spills and an evaporation loss of 22.8%. DO concentrations averaged 1.4 mg/l in tank A and 1.6 mg/l in tank B for the entire period. As loading rates increased, average DO concentrations tended to decline, but a positive DO residual was maintained at all times. OUR ranged between 27 and 660 mg/l/hr. Average uptake rates for the last three phases were 176 in tank A and 110 mg/l/hr in tank B representing an average daily respiration rate of 45 kg O_2/day (99 lb O_2/day) for both tanks. Oxygen supplied to the system averaged 37 kg/day (82 lb/day) in tank A and 26 kg/day (57 lb/day) in tank B. The oxygen transfer efficiency for the last three phases was 67% with a minimum of 49% in tank A during phase five and a maximum of 85% in tank A during phase three.

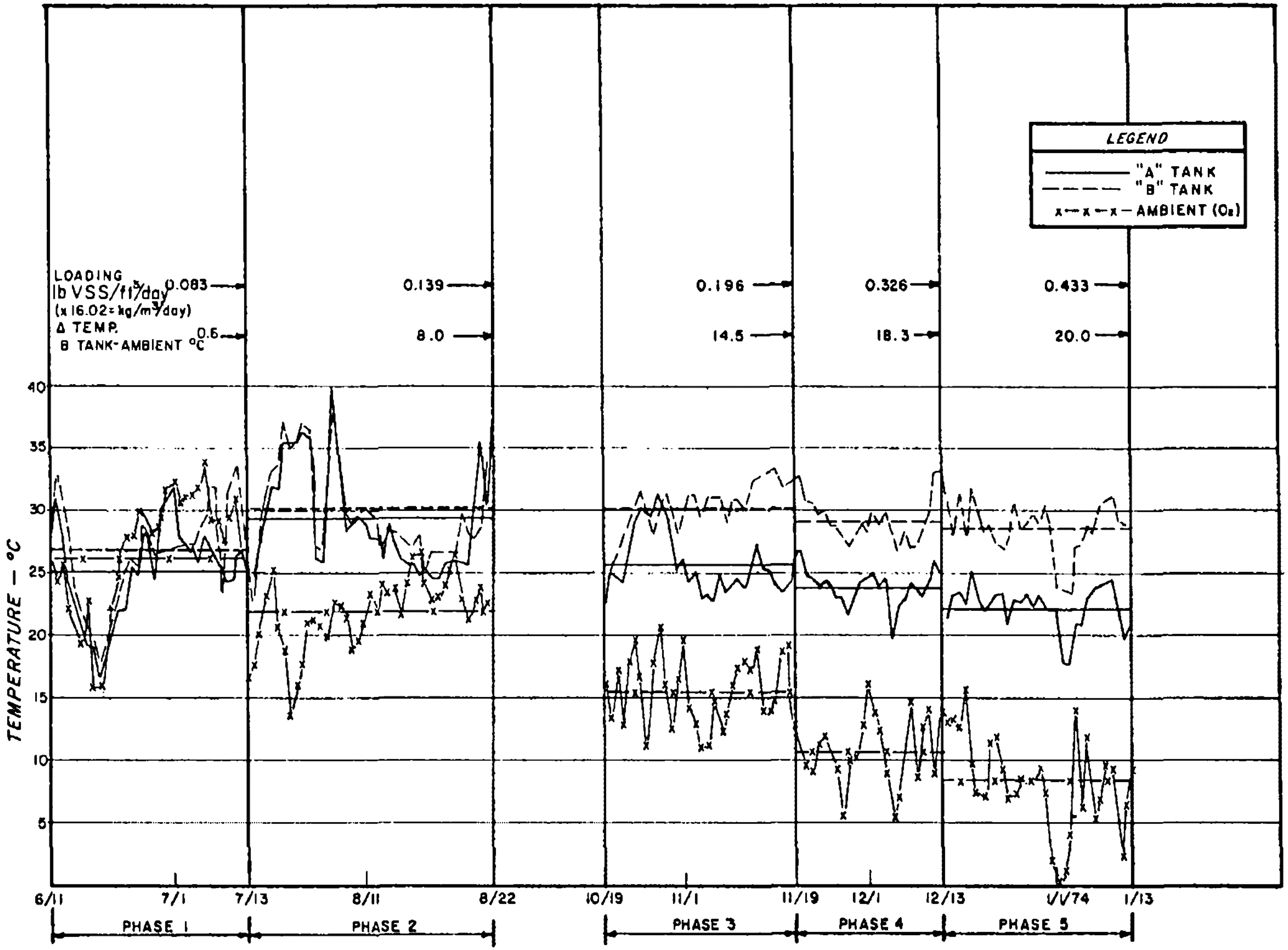


Fig. 51. Pure oxygen flow through test biomass and oxygen temperature versus time

Table 29. Pure oxygen digester flow through pilot plant (FAD) - field data

PHASE		VOLUMETRIC DATA (GAL/DAY)(1)				TEMPERATURE °C			OXYGEN DATA												
									DO (mg/l)		UPTAKE mg/l/hr		lb/DAY RESPIRED(2)			lb/DAY SUPPLIED(2)			% TRANSFER EFFICIENCY		
		FEED	WASTE	SPILLS	EVAP. CALC.	TANK A	TANK B	OXYGEN	TANK A	TANK B	TANK A	TANK B	TANK A	TANK B	TOTAL	TANK A	TANK B	TOTAL	TANK A	TANK B	TOTAL
I	MEAN	129	60	26	43	25.1	26.8	26.3	2.1	3.2	N.A.	N.A.	N.A.	N.A.	N.A.	63	61	124	N A	N A	N A
	MIN.	0	0	0	-	16.5	17.5	15.7	0.1	0.2	-	-	-	-	-	20	46	-	-	-	-
	MAX.	250	225	615	-	31.7	33.3	33.9	8.7	19.5	-	-	-	-	-	105	115	-	-	-	-
II	MEAN	220	161	4	55	29.3	30.1	21.9	2.1	1.9	N.A.	N.A.	N.A.	N.A.	N.A.	49	54	103	N A	N A	N A
	MIN.	0	0	0	-	24.7	23.7	13.5	0.2	0.1	-	-	-	-	-	33	33	-	-	-	-
	MAX.	330	374	150	-	40.3	39.5	26.7	4.3	4.4	-	-	-	-	-	94	137	-	-	-	-
III	MEAN	335	252	8	75	25.8	30.3	15.5	1.8	2.0	145.1	87.4	50	30	80	59	63	122	85	48	66
	MIN.	157	154	0	-	22.7	24.5	10.7	0.3	0.3	27	12	9	4	-	47	39	-	-	-	-
	MAX.	539	459	139	-	31.3	33.5	20.6	14.6	15.0	562	660	195	226	-	90	94	-	-	-	-
IV	MEAN	514	415	0	99	23.9	29.0	10.7	0.4	0.3	169.8	124.2	59	42	101	88	53	141	67	79	72
	MIN.	452	367	0	-	19.7	24.0	5.1	0.2	0.2	108	42	38	14	-	32	28	-	-	-	-
	MAX.	623	597	3	-	26.7	33.2	16.0	0.8	1.0	276	270	96	92	-	165	75	-	-	-	-
V	MEAN	640	525	2	113	22.3	28.6	8.4	0.5	0.5	211.9	118.6	74	41	115	152	55	207	49	75	56
	MIN.	539	399	0	-	17.7	23.5	-2.9	0.3	0.3	126	54	44	18	-	118	43	-	-	-	-
	MAX.	704	689	55	-	25.2	32.0	15.6	1.3	1.7	375	216	130	74	-	178	98	-	-	-	-
AVG 159 DAYS		377	283	8	86	25.3	29.0	16.6	1.4	1.6	176	110	61	38	99	82	57	139	67	67	67

(1) gal/day x 3.785 = l/day

(2) lb/day x 0.454 = kg/day

Solids Data

Table 30 summarizes VSS reductions in relation to loading rates. The average loading rate for all five phases was 3.76 kg VSS/m^3/day (0.234 lb VSS/ft^3/day). SRT declined from 63.3 days during phase one to 7.9 days in phase five, averaging 13.7 days. Hydraulic detention time declined from 22.3 days in phase one to 5.4 days in phase five averaging 9.1 days. VSS to the system increased from an average 7.3 kg/day (38 lb/day) in phase one to 90.8 kg/day (200 lb/day) in phase five, averaging 49.0 kg/day (108 lb/day). Waste VSS from the system including spills and foaming losses averaged 8.6 kg/day (19 lb/day) in phase one, increasing to 54.9 kg/day (121 lb/day) in phase five and averaging 28.8 kg/day (63.4 lb/day). VSS inventory in both tanks remained relatively constant, averaging 388 kg (855 lb) during phase one and increasing to 418 kg (921 lb) during phase five for an average increase of 0.16 kg/day (0.36 lb/day).

The amount of oxygen respired per lb VSS reduced declined from 1.94 in phase three to 1.49 in phase five, averaging 1.7. The amount of oxygen supplied per lb of VSS reduced which reflects the oxygen transfer efficiency, declined from 6.93 lb during phase one when severe foaming and plugging problems were experienced to a minimum of 2.37 in phase four,averaging 3.1 lb.

VSS reductions in the digester increased from 8.13 kg/day (17.9 lb/day) in phase one to 35.1 kg/day (77.3 lb/day) in phase five, averaging 20.2 kg/day (44.6 lb/day). Percent VSS reduced declined from 47.1% at the lowest loading rate to 38.8% at the highest loading rate averaging 42.7%.

Laboratory Data

Experimental data for the flow-through test with the FAD are presented in Tables 31, 32 and 33. Table 31 summarizes influent loadings to the digester, Table 32 summarizes effluent wasting from the digester and Table 33 compares the percent change between influent and effluent. TS declined by 8.1%, TVS declined by 14.9%, TSS declined by 21.3%, VSS declined by 27.2% while TDS increased by 173%.

Table 30. Pure oxygen digester flow through pilot plant (FAD) - performance data

PHASE		LOADING lb VSS/ft³/day(1)	FEED lb/day(2)	WASTE lb/day (2)	INVENTORY Δ lb/day(2)	lb (2)	RETENTION TIME (DAYS) S R T	HYDRAULIC	OXYGEN/VSS REDUCED RESPIRED	SUPPLIED	AEROBIC DIGESTION lb/day(2)	percent
I	MEAN	0.083	38.0	19.0	+ 1.1	855	63.3	22.3	N.A.	6.93	17.9	47.1
	MIN.	0	0	0	-	-	-	18.8	-	-	-	-
	MAX.	0.135	81.9	171.5	-	-	-	28.2	-	-	-	-
II	MEAN	0.139	64.3	35.8	+ 1.1	884	25.3	15.7	N.A.	3.76	27.4	42.6
	MIN.	0	0	0	-	-	-	11.0	-	-	-	-
	MAX.	0.188	92.4	76.8	-	-	-	23.3	-	-	-	-
III	MEAN	0.196	90.3	52.9	- 3.8	806	16.6	10.7	1.94	2.96	41.2	45.6
	MIN.	0.092	42.3	31.2	-	-	-	6.4	-	-	-	-
	MAX.	0.293	134.9	98.0	-	-	-	21.9	-	-	-	-
IV	MEAN	0.326	150.1	88.3	+ 2.4	866	10.2	6.7	1.70	2.37	59.4	39.6
	MIN.	0.230	127.0	59.4	-	-	-	5.8	-	-	-	-
	MAX.	0.421	193.8	138.4	-	-	-	12.8	-	-	-	-
V	MEAN	0.433	199.2	120.9	+ 1.0	921	7.9	5.4	1.49	2.68	77.3	38.8
	MIN.	0.301	152.3	90.9	-	-	-	5.0	-	-	-	-
	MAX.	0.579	266.2	186.2	-	-	-	6.4	-	-	-	-
159 DAYS		0.235	108.4	63.4	+ 0.36	866	13.7	9.1	1.70	3.10	44.6	42.7

(1) lb VSS/ft^3/day x 16.02 = kg/m^3/day

(2) lb/day x 0.454 = kg/day

Table 31. Pure oxygen digester flow through pilot plant (FAD) - laboratory data - influent loading (mg/l unless other units indicated)

PHASE		SOLIDS TS	TVS	TSS	VSS	TDS (calc.)	PERCENT VSS/TSS	COD	NITROGEN TKN	NH_4-N	NO_3-N	TOTAL P	ALK. as $CaCO_3$	pH (Units)	COND. µmho/cm^2	GREASE PERCENT	FECAL COLI no./ml
I	MEAN	47,930	37,150	45,640	35,350	2,290	77.5	55,010	3,450	180	0.90	1,150	2,320	6.5	1,790	-	-
	MIN.	41,240	-	38,700	27,200	-	-	42,900	2,930	60	0.01	754	1,740	6.1	1,060	-	-
	MAX.	62,440	-	60,000	44,500	-	-	76,800	3,980	285	2.86	2,680	3,330	7.4	2,520	-	-
II	MEAN	48,630	37,740	45,680	35,470	2,950	77.6	51,120	3,430	210	0.32	1,280	2,230	6.6	1,680	-	-
	MIN.	34,180	-	31,000	24,500	-	-	34,600	2,380	50	0.01	684	1,560	6.4	1,130	-	-
	MAX.	58,860	-	56,500	50,600	-	-	70,800	4,420	350	1.59	2,780	3,430	7.4	2,580	-	-
III	MEAN	43,070	35,530	39,230	32,360	3,840	82.5	51,840	3,590	127	0.23	1,880	1,670	6.5	1,870	7.4	37.0 x 10^6
	MIN.	36,200	-	32,900	27,600	-	-	43,200	3,070	36	0.01	800	1,370	6.1	1,150	-	
	MAX.	62,300	-	56,500	47,600	-	-	72,800	5,050	320	1.12	2,910	2,160	6.8	3,110	-	
IV	MEAN	45,350	37,960	41,830	35,020	3,520	83.7	56,380	3,940	120	0.21	1,120	1,970	6.6	1,410	17.8	16.0 x 10^6
	MIN.	38,600	-	35,200	31,800	-	-	45,600	3,420	40	0.01	900	1,340	6.4	980	-	
	MAX.	58,000	-	49,200	43,100	-	-	69,400	4,760	260	0.65	1,300	2,120	6.9	2,060	-	
V	MEAN	48,140	40,000	44,860	37,290	3,280	83.1	61,360	3,990	165	0.10	1,110	1,710	6.5	1,620	7.4	15.7 x 10^6
	MIN.	36,800	-	30,500	26,700	-	-	46,600	3,680	39	0.01	600	1,330	6.2	1,070	-	
	MAX.	62,800	-	58,900	47,000	-	-	70,100	4,330	385	0.15	1,460	2,860	6.9	2,760	-	
159 DAYS	AVG.	46,620	37,675	43,450	35,100	3,180	80.8	55,140	3,680	160	0.35	1,310	1,980	6.6	1,670	10.9	23.0 x 10^6

Table 32. Pure oxygen digester flow through pilot plant (FAD) - laboratory data effluent waste

PHASE		SOLIDS						COD	NITROGEN			TOTAL P	ALK. as $CaCO_3$	pH (Units)	COND. µmho/cm²	GREASE PERCENT	FECAL COLI no./ml
		TS	TVS	TSS	VSS	TDS (calc.)	PERCENT VSS/TSS		TKN	NH_4-N	NO_3-N						
I	MEAN	44,440	31,830	37,040	24,870	7,400	67.1	40,180	3,060	860	3.60	1,350	2,450	6.8	4,550	-	-
	MIN.	45,900	-	31,200	20,400	-	-	33,000	2,230	200	0.01	608	1,840	6.2	2,840	-	-
	MAX.	49,600	-	43,400	29,000	-	-	53,300	3,680	1,600	14.8	2,080	3,410	7.4	7,280	-	-
II	MEAN	45,180	31,130	37,950	26,140	7,230	68.9	42,430	3,040	805	0.60	1,270	4,200	7.2	3,720	-	-
	MIN.	42,400	-	28,900	21,400	-	-	34,700	2,750	290	0.01	528	3,040	6.4	3,000	-	-
	MAX.	52,300	-	43,500	31,200	-	-	49,900	3,360	1,300	4.48	2,600	4,820	7.9	5,620	-	-
III	MEAN	38,180	30,390	30,780	24,510	7,400	79.6	41,410	2,990	300	0.22	1,930	1,710	6.5	3,040	7.8	4.7 x 10^6
	MIN.	36,100	-	24,400	20,800	-	-	35,600	2,140	145	0.01	1,340	1,430	6.1	2,480	-	
	MAX.	41,800	-	38,600	30,900	-	-	50,600	3,500	650	0.60	2,880	2,500	7.0	4,600	-	
IV	MEAN	41,310	33,710	30,980	25,280	10,330	81.6	47,100	3,590	650	0.47	1,000	2,890	6.9	3,860	12.9	5.9 x 10^6
	MIN.	39,800	-	21,000	17,600	-	-	36,000	3,030	250	0.01	970	2,760	6.4	2,620	-	
	MAX.	42,400	-	36,600	29,500	-	-	53,800	4,110	970	1.14	1,420	3,010	7.2	5,710	-	
V	MEAN	42,150	33,420	34,130	27,070	8,020	79.3	52,300	3,690	680	0.36	1,300	3,120	6.8	4,560	7.4	5.6 x 10^6
	MIN.	39,700	-	26,500	22,100	-	-	43,600	2,240	490	0.01	600	2,760	6.6	3,820	-	
	MAX.	49,100	-	41,000	32,400	-	-	59,700	4,030	960	1.17	1,520	3,770	7.0	5,790	-	
159 DAYS	AVG.	42,850	32,050	34,180	25,570	8,680	74.8	44,680	3,270	660	1.05	1,370	2,880	6.8	3,950	9.4	5.4 x 10^6

Table 33. Pure oxygen digester flow through pilot plant (FAD) - laboratory data influent loading versus effluent waste percent change

PHASE	SOLIDS						COD	NITROGEN			TOTAL P	ALK. as $CaCO_3$	pH (units)	COND. μmho/cm^2	GREASE PERCENT	FECAL COLI no./ml
	TS	TVS	TSS	VSS	TDS (calc.)	PERCENT VSS/TSS		TKN	NH_4-N	NO_3-N						
I	-7.3	-14.3	-19.8	-29.7	+223.1	-10.4	-27.0	-11.3	+377.8	+300	+17.4	+5.6	+0.3	+154.2	N.A.	N.A
II	-7.1	-17.5	-16.9	-26.3	+145.1	- 8.7	-17.0	-11.3	+283.3	+87.5	-0.8	+88.3	+0.6	+121.4	N.A.	N A
III	-11.4	-14.5	-21.5	-24.3	+92.7	- 2.9	-20.1	-16.7	+136.2	-4.4	+2.7	+2.4	0	+62.6	+5.4	-87.3 x 10^6
IV	-8.9	-11.2	-25.9	-27.8	+193.5	- 2.1	-16.5	-8.9	+441.7	+123.8	-10.7	+46.7	+0.3	+173.8	-27.5	-63.1 x 10^6
V	-12.5	-16.5	-23.9	-27.4	+144.5	- 3.8	-14.8	-7.5	+312.1	+260	+17.1	+82.5	+0.3	+181.5	0	-64.3 x 10^6
AVG. 159 DAYS	-8.1	-14.9	-21.3	-27.2	+173.0	- 6.0	-19.0	-11.1	+312.5	+200	+4.6	+45.5	+0.2	+136.5	-13.8	-76.5 x 10^6

The VSS/TSS ratio declined by an average 6.0% for all phases with a range of 2.1% to 10.4%. COD reduction averaged 19.0%. Nitrogen forms showed a decrease of 11.1% for TKN while ammonium-N increased by 312.5% and nitrates increased by 200%. Although the increase in ammonium-N solubilization was substantial, the absolute concentration of nitrates in the effluent never exceeded 3.6 mg/l. Total phosphorus increased by only 4.6%. Alkalinity increased by +45.5% and pH increased by 0.2 units. Conductivity increased by +136.5% and TDS by 173.0%. The change in grease content between influent and effluent for the three periods that were analyzed indicates a reduction of -13.8%. Fecal coliforms declined by an average of 76.5%.

Invertebrate Analysis

Tables 34 and 35 present the invertebrate biomass concentrations (VSU) for tanks A and B respectively. Tank A was analyzed during phases 1, 2 and 3 only, whereas tank B was analyzed for all five phases. Table 36 summarizes the average invertebrate concentrations for each of the five phases in both tanks. Table 37 expresses the invertebrate biomass inventory as a percent distribution while Table 38 expresses the invertebrate biomass as a percent of the VSS under oxygenation. It is evident that the invertebrate biomass declined considerably after being transferred from tank A to tank B. Tank A data reflect the biomass population distribution of the activated sludge loaded to the system, whereas tank B biomass is more representative of the stabilized populations that are attained after substantial detention times. The total invertebrate wet weight in tank A averaged 13.8 g/l and declined by 83% to 2.4 g/l in tank B.

Rotifers and amoeba were observed in tank A but never in tank B. Flagellates increased on a percent distribution basis from 5.9% in tank A to 12.9% in tank B, motile ciliates averaged 55% of the total invertebrate biomass in both tanks, sessile ciliates increased from 14% in tank A to 32.5% in tank B, and rotifers, amoeba and nematodes did not appear at all in tank B. Flagellates as a percent of VSS declined from 0.18% in tank A to 0.08% in tank B, sessile ciliates declined from 1.03% in tank A to 0.35% in tank B, rotifers declined from 2.4% in tank A to zero in tank B, and amoeba declined to zero in tank B. Whereas 4.17% of the VSS in tank A consisted of invertebrates, they declined to 0.95% in tank B, representing a decrease of 77%. This decrease indicates that the conditions of crowding

Table 34. Pure oxygen digester flow through pilot plant (FAD) - invertebrate biomass in tank A - VSU (ml/l)

PHASE/DATE		FLAGELLATES	MOTILE CILIATES	SESSILE CILIATES	ROTIFERS	AMOEBA	NEMATODES	TOTALS	ECOLOGICAL DIVERSITY INDEX OBSERVED/TOTAL	PERCENT
I	6/4/73	0.50	0	0	0	0	0	0.50	1/6	16.7
	6/12 - 6/18/73	0	0	0	0	0	0	0	0	0
	6/20/73	0.10	0	0	0	0	0	0.10	1/6	16.7
	6/25/73	0.90	0	36.0	0	0	0	36.9	2/6	33.3
	6/27/73	0.30	0	0	0	0	0	0.3	1/6	16.7
	7/2/73	0	0	0	0	0	0	0	0	0
	7/10/73	0.5	0	0	0	0	0	0.5	1/6	16.7
II	7/16/73	2.90	0	0	0	0	0	2.9	1/6	16.7
	7/18/73	0.20	0	0	0	0	0	0.2	1/6	16.7
	7/23/73	0.90	3.3	10.0	0	0	0	14.2	3/6	50.0
	7/25/73	0	0	0	0	0	0	0	0	0
	7/30/73	0.50	0	0	0	0	0	0.50	1/6	16.7
	8/1/73	0	2.2	2.0	0	0	0	4.2	2/6	33.3
	8/6/73	0.40	13.0	0	0	0	0	13.4	2/6	33.3
	8/8/73	0	0	0	0	0	0	0	0	0
	8/13/73	0.40	1.1	0	0	0	0	1.5	2/6	33.3
	8/15/73	0	7.60	0	0	0	0	7.60	1/6	16.7
	8/22/73	0	0	0	0	0	0	0	0	0
	8/24/73	0	0	0	0	0	0	0	0	0
III	10/19/73	0	3.3	6.0	0	0	0	9.3	2/6	33.3
	10/24/73	0.30	13.0	2.0	0	0	0	15.3	3/6	50.0
	10/26/73	0.80	0	14.0	0	0.50	0	15.3	3/6	50.0
	10/29 - 10/31/73	0	0	0	0	0	0	0	0	0
	11/7/73	5.40	1.10	6.0	0	0	0	12.5	3/6	50.0
	11/12/73	0	0	4.0	167.0	0	0	171.0	2/6	33.3
	11/14/73	2.20	0	0	0	0	0	2.2	1/6	16.7

Table 35. Pure oxygen digester flow through pilot plant (FAD) - invertebrate biomass in tank B - VSU (ml/l)

PHASE/DATE	TAXONOMIC GROUP	FLAGELLATE	MOTILE CILIATES	SESSILE CILIATES	ROTIFERS	AMOEBA	NEMATODES	TOTALS	ECOLOGICAL DIVERSITY INDEX OBSERVED/TOTAL	PERCENT
I	6/4/73	0.50	0	0	0	0	0	0.5	1/6	16.7
	6/12 - 6/27/73	0	0	0	0	0	0	0	0	0
	7/2/73	0.10	0	0	0	0	0	0.1	1/6	16.7
	7/10/73	0	2.2	2.0	0	0	0	4.2	2/6	33.3
II	7/16/73	2.3	0	0	0	0	0	2.3	1/6	16.7
	7/18/73	0.20	0	0	0	0	0	0.2	1/6	16.7
	7/23 - 7/25/73	0	0	0	0	0	0	0	0	0
	7/30/73	0.30	0	0	0	0	0	0.3	1/6	16.7
	8/1/73	.10	3.8	0	0	0	0	3.9	2/6	33.3
	8/6 - 8/8/73	0	0	0	0	0	0	0	0	0
	8/13/73	2.40	2.2	0	0	0	0	4.6	2/6	33.3
	8/15 - 8/22/73	0	0	0	0	0	0	0	0	0
III	10/19/73	0	3.3	6.0	0	0	0	9.3	2/6	33.3
	10/24/73	0.2	4.3	2.0	0	0	0	6.5	3/6	50.0
	10/26 - 11/12	0	0	0	0	0	0	0	0	0
	11/14/73	0.3	0	0	0	0	0	0.3	1/6	16.7
IV	11/20/73	0	0	6.0	0	0	0	6.0	1/6	16.7
	11/23 - 11/25/73	0	0	0	0	0	0	0	0	0
	11/27/73	0	6.5	0	0	0	0	6.5	1/6	16.7
	12/3/73	0.10	0	0	0	0	0	0.10	1/6	16.7
	12/7 - 12/12/73	0	0	0	0	0	0	0	0	0
V	12/14/73	0	3.3	4.0	0	0	0	7.3	2/6	33.3
	12/19/73	0	2.2	0	0	0	0	2.2	1/6	16.7
	12/27 - 12/31/73	0	0	0	0	0	0	0	0	0
	1/5/74	0	5.4	0	0	0	0	5.4	1/6	16.7
	1/8/74	0.10	1.1	0	0	0	0	1.2	2/6	33.3
	1/10/74	0	0	0	0	0	0	0	0	0

Table 36. Pure oxygen digester flow through pilot plant (FAD) - invertebrate biomass in tank A and B averages -VSU (ml/l)

PHASE	FLAGELLATE	MOTILE CILIATE	SESSILE CILIATE	ROTIFER	AMOEBA	NEMATODE	TOTALS
PHASE I							
Tank "A"	.3	0	5.1	0	0	0	5.4
Tank "B"	.2	.6	.5	0	0	0	1.3
PHASE II							
Tank "A"	.3	2.3	1.0	0	0	0	3.6
Tank "B"	.7	.8	0	0	0	0	1.5
PHASE III							
Tank "A"	1.2	2.5	4.6	23.9	0.1	0	32.3
Tank "B"	.1	1.9	2.0	0	0	0	4.0
PHASE IV							
Tank "B"	0	1.3	1.2	0	0	0	2.5
PHASE V							
Tank "B"	0	2.0	0.7	0	0	0	2.7
AVERAGE							
Tank "A"	0.6	1.6	3.6	8.0	0.03	0	13.8
Tank "B"	0.2	1.3	0.9	0	0	0	2.4

Table 37. Pure oxygen digester flow through pilot plant (FAD) - invertebrate biomass percent distribution - VSU basis

PHASE	FLAGELLATE	MOTILE CILIATE	SESSILE CILIATE	ROTIFER	AMOEBA	NEMATODE	TOTALS
PHASE I							
Tank "A"	5.6	94.4	0	0	0	0	100
Tank "B"	15.4	46.2	38.5	0	0	0	100
PHASE II							
Tank "A"	8.3	63.9	27.8	0	0	0	100
Tank "B"	46.7	53.3	0	0	0	0	100
PHASE III							
Tank "A"	3.7	7.7	14.2	74.0	3.1	0	100
Tank "B"	2.5	47.5	50.0	0	0	0	100
PHASE IV							
Tank "B"	0	52.0	48.0	0	0	0	100
PHASE V							
Tank "B"	0	74.1	25.9	0	0	0	100
AVERAGE							
Tank "A"	5.9	55.3	14.0	23.8	1.0	0	100
Tank "B"	12.9	54.6	32.5	0	0	0	100

Table 38. Pure oxygen digester flow through pilot plant (FAD) invertebrate biomass as percent of VSS under oxygenation (dry weight basis)

PHASE	FLAGELLATE	MOTILE CILIATE	SESSILE CILIATE	ROTIFER	AMOEBA	NEMATODE	TOTALS
PHASE I							
Tank "A"	.085	0	1.4	0	0	0	1.5
Tank "B"	.080	0.24	0.20	0	0	0	0.5
PHASE II							
Tank "A"	.085	0.65	0.28	0	0	0	1.0
Tank "B"	.27	0.31	0	0	0	0	0.6
PHASE III							
Tank "A"	0.37	0.77	1.42	7.4	0.03	0	10.0
Tank "B"	0.04	0.78	0.82	0	0	0	1.6
PHASE IV							
Tank "B"	0	0.51	0.47	0	0	0	1.0
PHASE V							
Tank "B"	0	0.74	0.26	0	0	0	1.0
AVERAGE							
Tank "A"	0.18	0.47	1.03	2.47	0.01	0	4.17
Tank "B"	0.08	0.52	0.35	0	0	0	0.95

in this system were not conducive to growth and reproduction of these organisms.

Viable Biomass (ATP) Analysis

The viable portion of the aerobic digester biomass was quantified as the volatile portion of the suspended solids in the initial phases of this study. The biodegradable VSS was determined by an arbitrary calculation for the batch tests only. No simple, accurate method of distinguishing between viable and non-viable organic matter was available at the start of this project. Previous attempts to determine a specific measure of active biomass such as standard plate counts, organic carbon analysis, DNA, organic nitrogen or protein, rate of oxygen utilization or dehydrogenase enzyme activity were limited in their application by time consuming and sophisticated techniques. Recent investigations (14) have shown adenosine triphosphate (ATP) to be a specific measurement for biological activity in the activated sludge process. New instrumentational methods for ATP analysis have proven to be both rapid and simple.

ATP measurement is based on the firefly reaction where

$$\text{luciferin (reduced)} + \text{ATP} + O_2 \longrightarrow \text{luciferin (oxidized)} + \text{pyrophosphate} + \text{AMP} + H_2O + \text{light.}$$

Two instruments that were used for ATP analysis included a Dupont luminescence biometer (15), and JRB Inc. ATP photometer (16). Concentrations as low as 10^{-8} mg/l could be analyzed directly after proper sample preparations. The JRB technique recommends extraction of the sample with tris buffer, while the Dupont instrument technique recommends the use of DMSO extraction. The DMSO extraction method yielded higher results than did the tris buffer extractions. For example, identical samples of aerobic digester influent yielded an average ATP concentration of 15.8 mg/l with the DMSO extraction versus 2.4 mg/l with the tris buffer extraction. Similarly, analysis of the aerobic digester effluent from tank B yielded 7.7 mg/l using DMSO as compared with 0.8 mg/l using tris buffer. Although the absolute concentration of ATP was significantly higher with DMSO, the rate of ATP reduction between the influent and effluent samples was similar with either method. Table 42 summarizes the ATP data for the period 12/14/73 -

3/15/74. At the completion of the pure oxygen FAD test on January 13, 1974, operation of the pilot plant was continued for additional ATP data collection. ATP analysis phases 6 and 7 using the FAD during the period January 14 - March 15, 1974 are included in Table 39.

ATP reduction during phase five averaged 64.5% compared with 69.9% in phase six and 65.5% in phase seven. ATP reduction during phases 5, 6 and 7 averaged 66.6% compared with 37.0% VSS reduced for the same three phases. ATP reduction/VSS reduction averaged 1.8. The consistency of these results is all the more remarkable in view of the fact that no good coefficient of correlation was obtained between VSS and ATP concentrations in any of the phases studied. Similarly, no significant correlations were found between OUR and ATP concentrations in the aerated biomass. The utility of ATP, as a measure of aerobic digestion performance, should be further investigated in future aerobic digestion studies.

Sludge Dewaterability

Table 40 presents vacuum filter leaf test data run on raw influent and digested effluent WAS samples from the pure oxygen pilot plant for the period 7/3/73 to 1/7/74. Vacuum filter performance was calculated on the basis of the chemical cost, divided by the concentration factor x the loading rate. The average influent TS averaged 4.8% as compared with 4.2% in the effluent. Optimal chemical dosage is defined as the lowest vacuum filter performance factor at the highest filter cake concentration. At the optimal dosage, the filter cake TS averaged 14.2% in the influent compared with 13.3% in the effluent. This represented an influent concentration factor of 3.0 compared with 3.2 for the effluent.

The chemical demand for optimum dewatering of the influent solids was 9.0% $FeCl_3$ and 19.2% lime compared with 13.7% $FeCl_3$ and 19.0% lime for the effluent.

At an average cost for $FeCl_3$ of $100/ton and $25/ton for lime, influent WAS chemical cost was $13.80 compared to $20.95 for digester effluent chemical cost. The loading rate at the optimal chemical dosage was 13.7 $kg/m^2/hr$ (2.8 $lb/ft^2/hr$) in the influent WAS and 13.2 $kg/m^2/hr$ (2.7 $lb/ft^2/hr$) in the effluent WAS. The vacuum filter performance which summarizes all of

Table 39. Pure oxygen digester flow through pilot plant - ATP data summary

PHASE		ATP CONCENTRATION (ng/l) INFLUENT	EFFLUENT	PERCENT ATP REDUCTION	ATP REDUCTION / VSS REDUCTION	PERCENT VSS REDUCED
V	MEAN	3.24	1.15	64.5	1.67	38.8
	MIN.	1.40	1.01			
	MAX.	5.07	1.28			
VI	MEAN	2.16	0.65	69.9	1.98	35.4
	MIN.	0.69	0.46			
	MAX.	4.54	0.86			
VII	MEAN	18.04	6.23	65.5	1.78	36.8
	MIN.	7.42	1.89			
	MAX.	32.16	11.32			

Phase V - 12/14/73 - 1/13/74 (Tris-Buffer Extraction Method)

Phase VI - 1/14/74 - 2/13/74 (Tris-Buffer Extraction Method)

Phase VII - 2/14/74 - 3/15/74 (D.M.S.O. Extraction Method)

Table 40. *Pure oxygen digester flow through pilot plant influent and effluent vacuum filter leaf performance*

DATE	SAMPLE	PERCENT TS FEED	PERCENT TS CAKE	CONC. FACTOR	PERCENT CHEMICALS $FeCl_3$	PERCENT CHEMICALS LIME	PERCENT CHEMICALS TOTAL	CHEMICAL COST ($/TON)	LOAD RATE (1) $lb/ft^2/hr$	VACUUM FILTER PERFORMANCE FACTOR (2)
7/3/73	Influent	4.8	14.5	3.0	4.7	20.0	24.7	9.70	1.1	2.9
		"	14.9	3.1	9.5	20.0	29.5	14.50	2.3	2.0
		"	15.5	3.2	9.5	30.0	39.5	17.00	3.8	1.4*
	Effluent	4.4	14.9	3.4	4.8	20.0	24.8	9.80	0.8	3.6
		"	14.7	3.3	9.5	20.0	29.5	14.50	1.4	3.1
		"	15.5	3.5	9.5	30.0	39.5	17.00	2.1	2.3*
8/1/73	Influent	5.1	13.5	2.6	4.6	9.8	14.4	7.05	1.1	2.5
		"	15.6	3.1	5.5	13.7	19.2	8.93	1.9	1.5
		"	15.5	3.0	7.1	15.7	22.8	11.03	2.6	1.4*
	Effluent	4.7	13.2	2.8	5.0	10.7	15.7	7.68	0.3	9.1
		"	15.0	3.2	7.7	17.1	29.8	11.98	1.3	2.9
		"	15.0	3.2	9.6	21.4	31.0	14.95	1.7	2.7*
11/10/73	Influent	4.4	10.4	2.4	4.6	9.1	13.7	6.88	0.8	3.6
		"	13.5	3.1	9.1	18.1	27.2	13.63	2.5	1.8*
		"	13.7	3.1	11.9	23.6	35.5	17.80	2.9	2.0
	Effluent	3.7	11.1	3.0	7.9	15.5	23.4	11.78	0.7	5.6
		"	10.9	2.9	11.8	23.4	35.2	17.65	1.4	4.3*
		"	10.8	2.9	9.8	19.6	29.4	14.70	0.9	5.6
11/13/73	Influent	5.7	12.9	2.3	4.3	8.7	13.0	6.48	1.4	2.0
		"	14.2	2.5	6.2	12.4	18.6	9.30	1.9	2.0*
		"	14.7	2.6	8.1	16.1	24.2	12.13	2.2	2.1
	Effluent	3.9	10.8	2.8	13.6	27.1	40.7	20.38	1.7	4.3
		"	10.9	2.8	16.3	32.6	48.9	24.45	1.8	4.9
		"	11.2	2.9	18.6	36.2	54.8	27.65	2.7	3.5*
11/26/73	Influent	4.4	11.6	2.6	6.8	13.5	20.3	10.18	1.5	2.6
		"	12.3	2.8	9.0	18.1	27.1	13.53	2.6	1.9*
		"	12.6	2.9	10.1	20.3	30.4	15.18	2.5	2.1
	Effluent	4.1	11.7	2.9	10.3	20.6	30.9	15.45	1.3	4.1
		"	12.3	3.0	14.6	29.2	43.8	21.90	2.1	3.5
		"	12.1	3.0	18.9	37.8	56.7	28.35	2.8	3.4*
12/10/73	Influent	4.6	13.1	2.8	6.5	12.9	19.4	9.73	1.4	2.5
		"	14.5	3.2	10.7	21.6	32.3	16.10	2.3	2.2
		"	14.3	3.1	16.2	32.3	48.5	24.28	4.6	1.7*
	Effluent	4.1	14.7	3.6	15.4	31.0	46.4	23.15	2.5	2.6
		"	14.4	3.5	17.5	36.9	54.4	26.73	3.7	2.1*
		"	14.1	3.4	22.7	45.4	68.1	34.05	3.9	2.6
12/20/73	Influent	4.9	11.9	2.4	10.2	19.4	29.6	15.05	5.8	1.1*
		"	13.3	2.7	8.5	15.4	23.9	12.35	2.2	2.1
		"	12.6	2.6	5.9	11.7	17.6	8.83	1.6	2.1
	Effluent	4.5	11.6	2.6	14.1	27.8	41.9	21.05	2.6	3.1
		"	13.3	3.0	16.0	31.4	46.4	23.85	3.6	2.2*
		"	12.6	2.8	11.3	22.4	33.7	16.90	2.1	2.9
1/2/74	Influent	5.0	14.2	2.8	9.6	19.2	28.8	14.40	3.1	1.7
		"	13.8	2.8	7.7	15.4	23.1	11.55	2.5	1.7
		"	14.5	2.9	5.8	11.5	17.3	8.68	2.1	1.4*
	Effluent	4.4	13.0	3.0	13.7	27.5	41.2	20.58	2.6	2.6*
		"	12.6	2.9	9.1	18.3	27.4	13.68	1.0	4.7
		"	13.0	3.0	11.4	22.9	34.3	17.13	1.8	3.2
1/7/74	Influent	4.1	15.1	3.7	9.8	19.7	29.5	14.73	2.5	1.6*
		"	12.1	3.0	7.8	15.8	23.6	11.75	2.0	2.0
	Effluent	4.2	10.0	3.4	9.5	19.0	28.5	14.25	0.6	7.0
		"	14.7	3.5	15.0	30.0	45.0	22.50	2.7	2.4
		"	15.0	3.6	20.0	40.0	60.0	30.00	4.1	2.0*
AVG (optimal dosage)	Influent	4.8	14.2	3.0	9.0	19.2	28.2	13.80	2.8	1.6
	Effluent	4.2	13.3	3.2	13.7	29.0	42.7	20.95	2.7	2.4

(1) $lb/ft^2/hr \times 4.88 = kg/m^2/hr$

(2) Vacuum filter performance factor = $\frac{\$/ton}{\text{conc. factor} \times \text{load rate}}$

(lowest factor = best performance)

these factors was 1.6 for the influent versus 2.4 in the effluent, (the smaller the factor, the better the performance). This represents a 50% increase in chemical costs of the effluent sample in order to obtain equivalent filter cake concentrations and loading rates.

If the data for chemical costs are plotted against loading rates as shown in Figure 60, two straight line equations are obtained:

y (effluent chemical cost) = 5.83 x loading rate +9.8 and
y (influent chemical cost) = 5.19 x loading rate -0.6.

EXPERIMENTAL RESULTS - PURE OXYGEN FLOW-THROUGH (RAD) TESTS

Stage 3 testing with RAD in a single tank commenced on March 6, 1974 and continued until May 6, 1974. The objectives of these tests were:

1. To demonstrate the capability of the RAD to aerobically digest thickened WAS without prescreening.

2. To demonstrate a high degree of O_2 transfer efficiency.

3. To demonstrate a high degree of VSS reduction.

The first objective was consistently achieved. No debris accumulation appeared, despite the removal of prescreening which was required with the FAD. The other two objectives were realized and are discussed in test runs 1 and 2. Experimental data for the flow-through RAD test are presented in Tables 41, 42 and 43. Table 41 summarizes the operating data, Table 42 summarizes the influent and effluent laboratory data, and Table 43 presents calculations of biomass reduction performance.

Run No. 1 of the stage 3 test series was loaded at 9.60 kg VSS/m^3/day (0.60 lb VSS/ft^3/day) while the loading for run No. 2 was reduced to 6.88 kg VSS/m^3/day (0.43 lb VSS/ft^3/day). DO concentration averaged 1.2 mg/l with range of 0.5 to 6.1 mg/l. OUR was substantially higher during the test run at the higher loading rate. The lb O_2 supplied/lb VSS reduced averaged 1.54 with a range of 1.36 to 1.71. This performance should be compared favorably with the flow-through FAD tests which averaged 3.1 lb O_2 supplied/lb VSS reduced. The RAD test results represented a 50% reduction in oxygen supply requirements compared with the FAD test results at identical loadings. The pounds of oxygen respired compared to pounds of oxygen supplied indicates an oxygen utilization of greater than 100%. This anomaly is attributed to oxygen uptake sampling and calculation methods previously discussed.

Table 41. Pure oxygen digester flow through pilot plant (RAD) - field data

TEST NO.	VOLUMETRIC DATA (gal/day)(1)		TEMPERATURE (°C)		OXYGEN					
					D O	UPTAKE	lb/day	lb/day(2)	OXYGEN/VSS DIG	
	FEED	WASTE	TANK B	OXYGEN	mg/l	mg/l/hr	RESPIRED	SUPPLIED	RESPIRED	SUPPLIED
1. MEAN	474	448	33	10	1.5	247	85	83	1.75	1.71
MIN.	365	348	27	2	0.5	141	48	39	-	-
MAX.	748	643	43	17	6.1	453	155	192	-	-
2. MEAN	397	346	32	19	0.8	189	65	43	N.A.	1.36
MIN.	313	296	25	9	0.4	111	38	33	-	-
MAX.	848	383	35	26	1.3	249	85	52	-	-
AVG. 57 Days	436	397	32.5	14.5	1.2	218	75	63	-	1.54

(1) gal/day x 3.785 = l/day

(2) lb/day x 0.454 = kg/day

Table 42. Pure oxygen digester flow through pilot plant (RAD)-influent and effluent laboratory data

TEST RUN	TSS (mg/l)	VSS (mg/l)
1. INFLUENT		
MEAN	43,200	35,200
MIN.	35,400	29,300
MAX.	51,400	42,200
EFFLUENT		
MEAN	31,850	24,600
MIN.	22,900	17,700
MAX.	42,200	31,700
PERCENT CHANGE INF vs EFF	- 26.3	- 30.1
2. INFLUENT		
MEAN	38,200	31,300
MIN.	31,500	26,900
MAX.	44,000	35,400
EFFLUENT		
MEAN	29,600	23,100
MIN.	23,700	20,000
MAX.	34,000	26,900
PERCENT CHANGE INF vs EFF	- 22.5	- 26.2

Table 43. Pure oxygen digester flow through pilot plant (RAD) - biomass reduction performance

TEST RUN	LOADING (1) lb VSS/ft^3/day	FEED lb/day (2)	WASTE lb/day (2)	INVENTORY (2) lb/day	INVENTORY (2) lb	RETENTION TIME (DAYS) SRT	RETENTION TIME (DAYS) HYDRAULIC	AEROB. DIG. lb/day (2)	AEROB. DIG. %
1. MEAN	0.60	137	92	-3.0	424	4.7	3.7	48.4	35.3
MIN.	0.47	108	64	-	-	3.1	2.3	-	-
MAX.	0.93	213	130	-	-	6.2	4.7	-	-
2. MEAN	0.43	99	66	+0.7	386	5.8	4.5	31.5	32.0
MIN.	0.34	79	59	-	-	5.2	4.1	-	-
MAX.	0.51	118	82	-	-	6.6	5.4	-	-
AVG 57 Days	0.515	118	79	-1.6	405	5.3	4.1	40.0	33.7

(1) lb VSS/ft^3/day x 16.02 = kg/m^3/day

(2) lb/day x 0.454 = kg/day

The average loading for both test periods was 8.25 kg VSS/m^3/day (0.515 lb VSS/ft^3/day). VSS loadings averaged 53.6 kg/day (118 lb/day) with an average wasting rate of 36.8 kg/day (79 lb/day). Inventory decreased by an average 0.73 kg/day (1.6 lb/day) for the 57 day period. During the test run 1, inventory declined by an average of 1.36 kg VSS/day (3.0 lb VSS/day) with an increase of 0.32 kg/day (0.7 lb/day) during the second test run. The SRT and hydraulic detention time averaged 5.3 days and 4.1 days respectively, indicating the feasibility of high volumetric loadings and low space requirements. VSS digestion averaged 33.7%.

The temperature differential between ambient oxygen and biomass was 13°C at the lower loading and 23°C at the higher loading. These temperature differentials are similar to those observed during the flow-through FAD test program.

The data obtained with the RAD represents a significant breakthrough in the technology of pure oxygen aerobic digestion. No other literature references are known indicating the existence of pure oxygen digestion systems capable of achieving a high degree of biomass reduction in thickened WAS at very high VSS loading rates and low oxygen utilization levels.

COMPARISON OF AIR AND OXYGEN PERFORMANCE

In order to make a comparison of the plant scale diffused air digestion performance with the pure oxygen pilot plant performance, the Metro diffused air data were recalculated by averaging data for months of approximately equivalent SRT and VSS loading rates. Table 44 summarizes the organic loadings versus the percent change between influent and effluent laboratory data. Table 45 summarizes the percent change between influent and effluent versus SRT.

While there is some overlapping of loading rates, between the ranges 7.9 to 29.8 days SRT or 1.34 to 3.0 kgVSS/m^3/day (0.084 to 0.187 lb VSS/ft^3/day), the extreme ranges of less than 8 days SRT for the air system and greater than 30 days SRT for the oxygen system do not overlap.

A major difference between the air and oxygen systems relates to the temperature ranges experienced with each system. Whereas air system temperatures were subject to sudden changes (between 11.5 and 32.2°C) the pure oxygen pilot plant system was conducted indoors and therefore not subject to cold temperature shock. Significant increases in biomass temperature occurred with the oxygen system, particularly during the initial batch tests. During batch test 1, the temperature increased from an initial 19.4°C to a high of 44°C, for an increase of 24.5°C. The sudden decline in OUR with an increase of temperatures above 40°C indicates that the mesophilic biomass may have been replaced by an incipient thermophilic bacterial culture. The intermediate temperature range of 40 to 50°C is apparently an inefficient range for accomplishing rapid VSS reduction because of time required for reestablishment of new dominant bacterial cultures. During the flow-through pure oxygen testing using the FAD, the biomass temperatures increased in direct relation to the loading rates, with the maximum increase of 20°C being experienced at the highest loading rate. A temperature increase of 23°C was attained when using the RAD at the highest loading rate. The ability to maintain high loading rates in thickened WAS suggests the possibility of thermophilic aerobic digestion with

Table 44. Diffused air digester laboratory data - organic loading versus percent change between influent and effluent

lb/VSS/ft^3/day (1)	TOTAL SOLIDS	SUSPENDED SOLIDS TSS	SUSPENDED SOLIDS VSS	TOTAL DISSOLVED SOLIDS	COD	NITROGEN-N NO_3x10^3	NITROGEN-N NH_4	NITROGEN-N TKN	CONDUCTIVITY μmo/cm^2	pH units	ALK. as $CaCO_3$
0.026 (a)	-28.7	-36.0	-39.3	+38.9	-42.1	+135	+77.3	-35.0	+46.0	-0.2	-36.5
0.052 (b)	-32.5	-46.8	-50.9	+98.5	-50.8	+200	+141.1	-32.9	+73.5	-0.45	-63.9
0.085 (c)	-26.9	-36.1	-42.6	+58.5	-42.8	+180	+90.0	-35.2	+45.1	-0.13	-32.3
0.147 (d)	-14.9	-18.1	-21.3	+16.2	-25.5	+0.19	+55.2	-11.8	+18.0	+0.05	+11.4
0.187 (e)	-10.6	-13.6	-14.6	+16.7	-18.1	+0.07	+12.9	-10.3	+12.5	0	+4.3

(1) lb VSS/ft^3/day x 16.02 = kg/m^3/day

Data Averaged From:

(a) April 1973

(b) October, November 1972

(c) August, September 1972, May, June 1973

(d) December 1972, March, July, August 1973

(e) January, February 1973

Table 45. Diffused air digester laboratory data - SRT versus percent change between influent and effluent

S R T (DAYS)	TOTAL SOLIDS	SUSPENDED SOLIDS		TOTAL DISSOLVED SOLIDS	COD	NITROGEN - N			CONDUCTIVITY $\mu mho/cm^2$	pH units	ALK. as $CaCO_3$
		TSS	VSS			$NO_3 x10^3$	NH_4	T.K.N.			
3.0 (a)	-11.0	-14.0	-15.8	+15.4	-19.0	+0.11	+20.5	-12.2	+13.4	0	+0.7
4.1 (b)	-15.9	-19.1	-22.3	+17.3	-27.0	+0.19	+61.7	-10.4	+19.0	+0.07	-8.5
6.3 (c)	26.0	-34.9	-40.5	+47.9	-42.0	+22.8	+97.1	-31.4	+31.9	-0.1	-27.8
8.6 (d)	-24.5	-31.5	-40.6	+40.2	-47.2	+230	+44.7	-33.3	+44.3	0	-13.5
12.2 (e)	-32.5	-46.8	-50.9	+98.5	-50.8	+200	+141	-32.9	+73.5	-0.45	-63.4
18.3 (f)	-31.0	-43.2	-48.7	+97.9	-45.0	+445	+121.4	-44.8	+72.3	-0.40	-60.0
29.8 (g)	-28.7	-36.0	-39.3	+38.9	-41.2	+135	+77.3	-35.0	+46.0	-0.20	-36.5

Data Averaged From:

(a) January, February, August 1973
(b) December 1972, March, July 1973
(c) August, September 1972
(d) June 1973
(e) October, November 1972
(f) May 1973
(g) April 1973

accelerated rates of VSS reduction if the oxygen system were to be insulated to conserve the heat generated. It would, however, be necessary to ensure that the thermophilic cultures were consistently maintained above the minimum temperatures required for optimal growth and development in order to avoid cycling between mesophilic and thermophilic conditions with subsequent unpredictability of biological performance.

Another difference between the air and oxygen system relates to settleability and the possibility of decanting. While the settling rate of the aerobically digested sludge from the diffused air system was relatively slow <0.92m/hr, the subsequent handling of the WAS with cationic polymers to obtain a thickened float precluded any additional solid-liquid separation by gravity settling in the pure oxygen system. No significant separation of the oxygen digested sludge was observed after several weeks settling time. Comparison of settleability rates between the air and oxygen systems was, therefore, not possible. A further difference between the air and oxygen systems relates to the influence of SRT prior to aerobic digestion or the ultimate rate of VSS reduction. While the SRT of the activated sludge prior to loading the aerobic digester appeared to have little influence on the rate of VSS reduced, the opposite was the case during the batch tests with pure oxygen. During batch test 3 when diffused air digested sludge was loaded to the pure oxygen pilot plant, a much lower rate of VSS reduction was observed than when undigested sludge was loaded to the digester. It appears that a major factor determining VSS reduction rates in the oxygen digester was the initial VSS/TSS ratio. The initial VSS/TSS ratio of the undigested WAS loaded to the oxygen digester averaged 82% with little seasonal variability. A significant reduction in the VSS/TSS ratio was noted in the diffused air digested sludge loaded to the oxygen pilot plant with subsequent reduction in digestion performance. The activated sludge system gets continual replenishment of organic substrate, with biosynthesis resulting in relatively high volatile fractions. During aerobic digestion of WAS, however, there is no external replenishment of soluble organic substrate. Endogenous respiration, thus ensures that the effluent from the aerobic digester will have a lower volatile solids ratio than the original sample. There does not appear to be any advantage to aerobic digestion in two stages, that is diffused air digestion followed by pure oxygen digestion. If a pure oxygen system is available, the best use of plant resources would indicate that the WAS be loaded directly to the oxygen system without an intermediary diffused air step.

No difference in odor potential between the sludges from the diffused air and pure oxygen systems was observed. The final volatile solids ratio obtained would determine the potential for odor generation, particularly if land spreading were the ultimate sludge disposal method. The possibility of anaerobic conditions causing odors should not be overlooked if the VSS fraction of the digested sludge is greater than 60%. A more quantitative measure of sludge stability than the evaluation of odor potentials is the specific oxygen uptake rate (K_r). Whereas in the oxygen batch tests K_r of less than 1.0 was achieved in 10 days, the flow through air and oxygen systems K_r ranged between 4 to 6. The high OUR above the endogenous respiration level was attributed to metabolic resynthesis oxygen requirements using lysed metabolites. No significant correlation between K_r and nitrification rate was observed with either the air or the oxygen system. Similarly, no relation was observed between increasing DO concentration and the rate of aerobic digestion up to 16.6 mg/l in the oxygen system and up to 6.0 mg/l in the diffused air system. Contrary to some statements in the literature[12] regarding the influence of DO concentration on digestion levels, it appeared that DO concentration was an effect rather than a cause of changing OUR. When OUR declined, DO concentrations tended to increase if the oxygen supply was constant. The specific oxygen uptake rate (K_r) averaged 7.1 for the air system compared with 5.0 in "A" tank and 4.3 in "B" tank of the pure oxygen system. On the basis of the differential between initial and final VSS/TSS ratios achieved in both the air and the oxygen digesters, an empirical standard for a stabilized sludge of K_r<5 appeared reasonable.

The percent reduction in the different solid forms achieved for both the air and oxygen flow-through systems is depicted in Figure 52. At loading rates above 2.4 kgVSS/m^3/day (0.15 lb VSS/ft^3/day), the percent reduction of VSS was greater with the oxygen systen than the air system. Conversely, at loading rates below 1.60 kgVSS/m^3/day (0.10 lb VSS/ft^3/day), the reduction of all solids forms was greater with the air system than the oxygen system. The degree of solubilization represented by TDS percent change between influent and effluent was greater at all loading rates for the oxygen system than for the air system. The oxygen system was, therefore, better able to maintain a high degree of VSS reductions at very high loading rates that could not be maintained in the air system because of oxygen transfer limitations. Figure 53 shows the change between influent and effluent VSS compared with COD and TKN for both air and oxygen as a function of organic loading rates and SRT. A very close

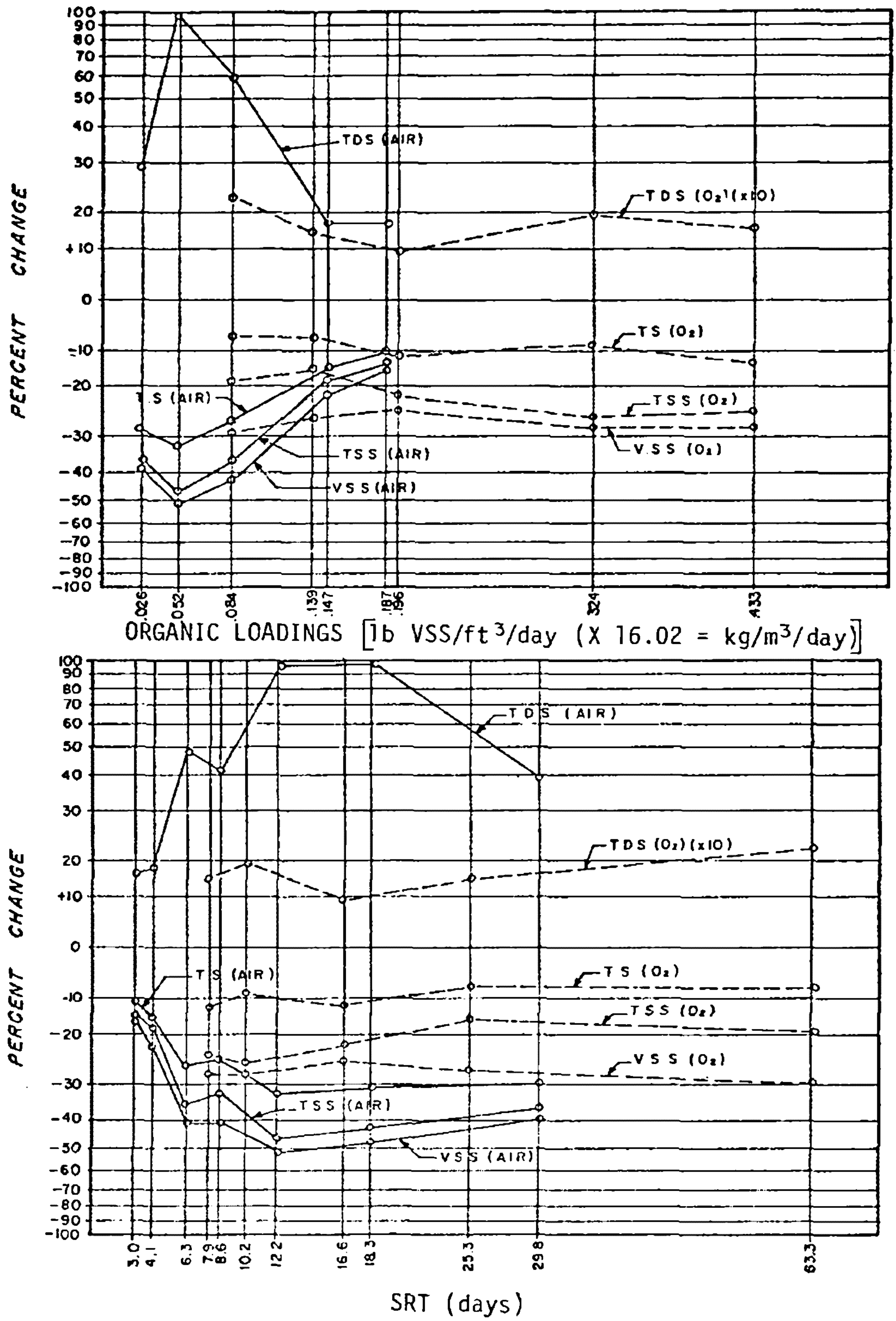


Fig. 52. Air versus oxygen performance-percent change in solids forms as a function of organic loadings and SRT

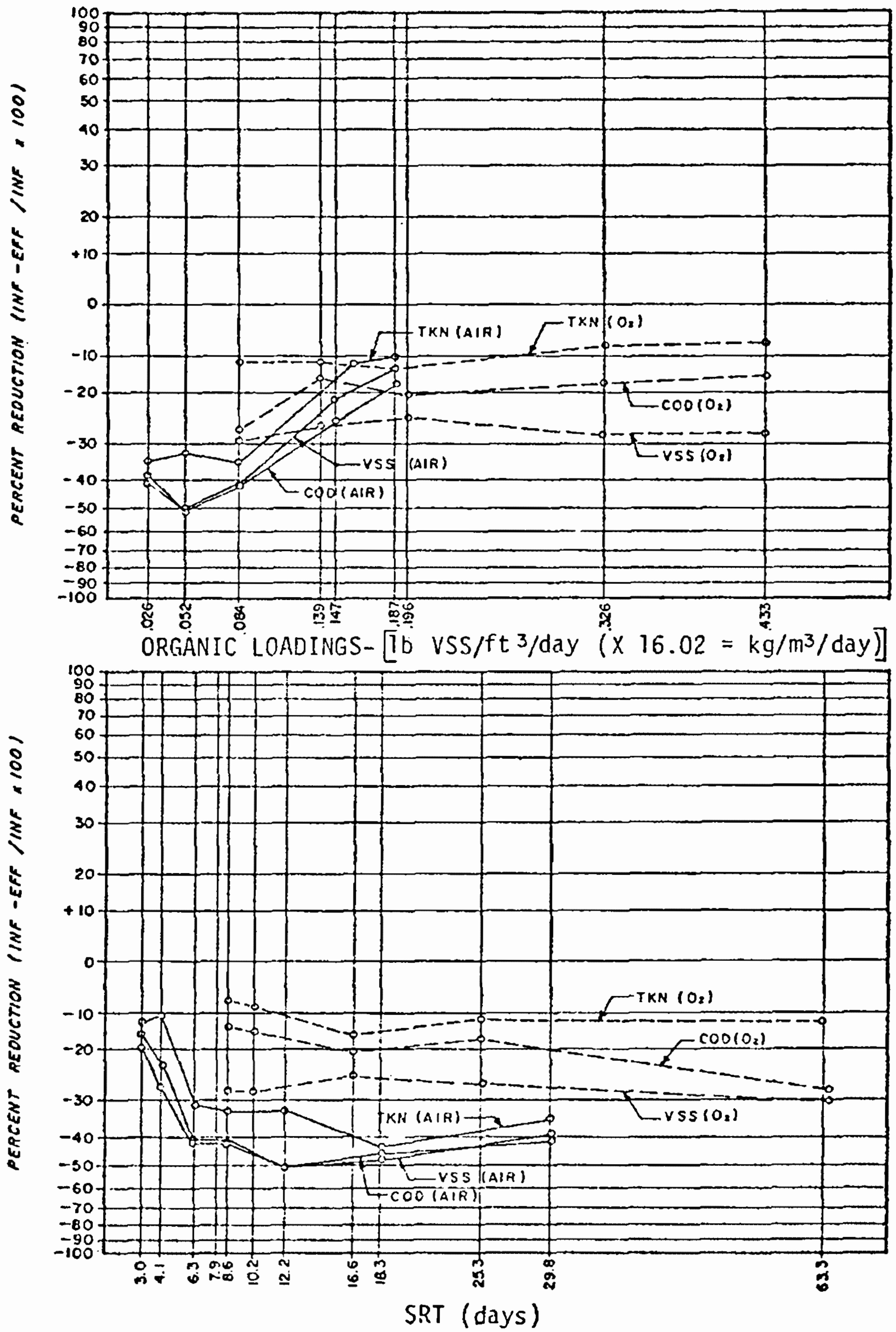


Fig. 53. Air versus oxygen performance-percent change in VSS, COD and TKN as a function of organic loadings and SRT

correlation was observed in percent reduction of all three parameters for both the air and oxygen systems. The highest rate of VSS or COD reduction occurred below loadings of 1.60 $kgVSS/m^3/day$ (0.1 lb $VSS/ft^3/day$) for the air system, whereas performance with the oxygen system was uniformly high throughout the entire loading range. For both the air and oxygen systems at identical loadings, TKN reductions were usually less than COD reductions, which in turn were generally less than VSS reductions. The ultimate potential of the oxygen system for reducing VSS was exhibited in the batch tests. During batch test 1 53.7% VSS reduction was achieved after 20 days compared with 53.4% in 14 days during batch test 2. In both these tests, VSS approached the maximum limit in half of the ultimate detention times. The high degree of correlation noted in the diffused air digester between percent VSS reduced and the time-temperature factor was also observed for the oxygen system (Figure 57). No additional benefit appeared to be gained by detaining sludge beyond 12 days at temperatures between 15-30°C.

The VSS/TSS reduction in the air digester averaged 5% compared with 6% for the pure oxygen flow-through tests. These volatile solids ratio reductions correlated well with the percent VSS reduced, which averaged 32% for the air digester and 41% for the oxygen flow-through FAD digester. Figure 54 shows the change between influent and effluent in conductivity and TDS for both air and oxygen systems as a function of organic loadings and SRT. For both systems, the best performance was directly correlatable with the highest differential in conductivity and TDS. Solubilization of suspended solids to TDS reached a peak at SRT of 18 days in the air system, while solubilization continued to increase in the oxygen system up to 63 days SRT. At identical organic loadings, the solubilization rate was always higher in the oxygen system than the air system. At loadings of 1.39 $kgVSS/m^3/day$ (0.19 lb $VSS/ft^3/day$), conductivity increased by 15% in the air digester compared with 60% increase in the oxygen digester. Conductivity appeared to be a simple and accurate analytical field method for measuring degree of aerobic stabilization achieved.

Conversion rates of organic nitrogen to nitrates, ammonium-N and nitrogen gas were significantly different in the oxygen and air digesters. During periods when temperature conditions were favorable for nitrification, most of the organic nitrogen conversion occurred as an increase in NO_3 in the air digester.

Approximately half of the organic nitrogen was converted to nitrate, while a fourth of the conversion appeared as an increase in ammonium-N concentration. The remainder of the conversion was due to denitrification during periods of low DO concentration. Figure 55 shows the change between influent and effluent in ammonium and nitrate percent increases in relation to organic loadings and SRT for both the oxygen and air digesters. Whereas a very good correlation was observed between nitrification and time-temperature factor above 20°C for the diffused air digester +0.96, no such correlation was observed for the oxygen digester. High nitrification rates were observed in several of the oxygen batch tests, but minimal nitrification occurred in the flow-through tests. It is assumed that the conditions of crowding due to the high biomass concentrations as well as air flotation polymer conditioning and high mixing energy did not provide a suitable environment for rapid growth and reproduction of nitrifying bacteria in the oxygen digester. In the air digester, the highest rate of nitrification was observed when the temperature corrected OUR (K_{20}) was at a minimum. No such correlation was observed, however, with the oxygen digester. Nitrate concentrations in the air digester increased by a factor of 10^5 between influent and effluent at an SRT of 8.6 days. The highest nitrate levels observed in any of the oxygen phases was less than 5 mg/l NO_3-N. Ammonium concentrations were significantly higher and NO_3-N concentrations were significantly lower in the oxygen digester than the air digester at equivalent loading rates. At organic loadings of 3.0 kg VSS/m^3/day (0.187 lb VSS/ft^3/day), ammonium-N increased in the air system by only 12% versus 150% in the oxygen system. Increases in nitrate concentration in the diffused air digester were observed to occur concurrently with increases in ammonium-N concentration up to a SRT of 10 days and then declined in parallel up to a SRT of 30 days. The oxygen system appeared to convert more organic nitrogen to ammonium-N than the air system at equivalent loadings, while more of the ammonium-N was oxidized to nitrates in the air digester.

The effect of nitrification on changes in alkalinity and pH are apparent in Figure 56. In the air system for organic loading rates of (<2.24 kg VSS) m^3/day (<0.14 lb VSS/ft^3/day), alkalinity and pH were lower in the effluent than the influent. At loadings above 2.4 kg VSS/m^3/day (0.15 lb VSS/ft^3/day), nitrification ceased in the air digester causing both alkalinity and pH to increase in the effluent sample. As nitrification essentially did not occur in the flow-through oxygen digester,

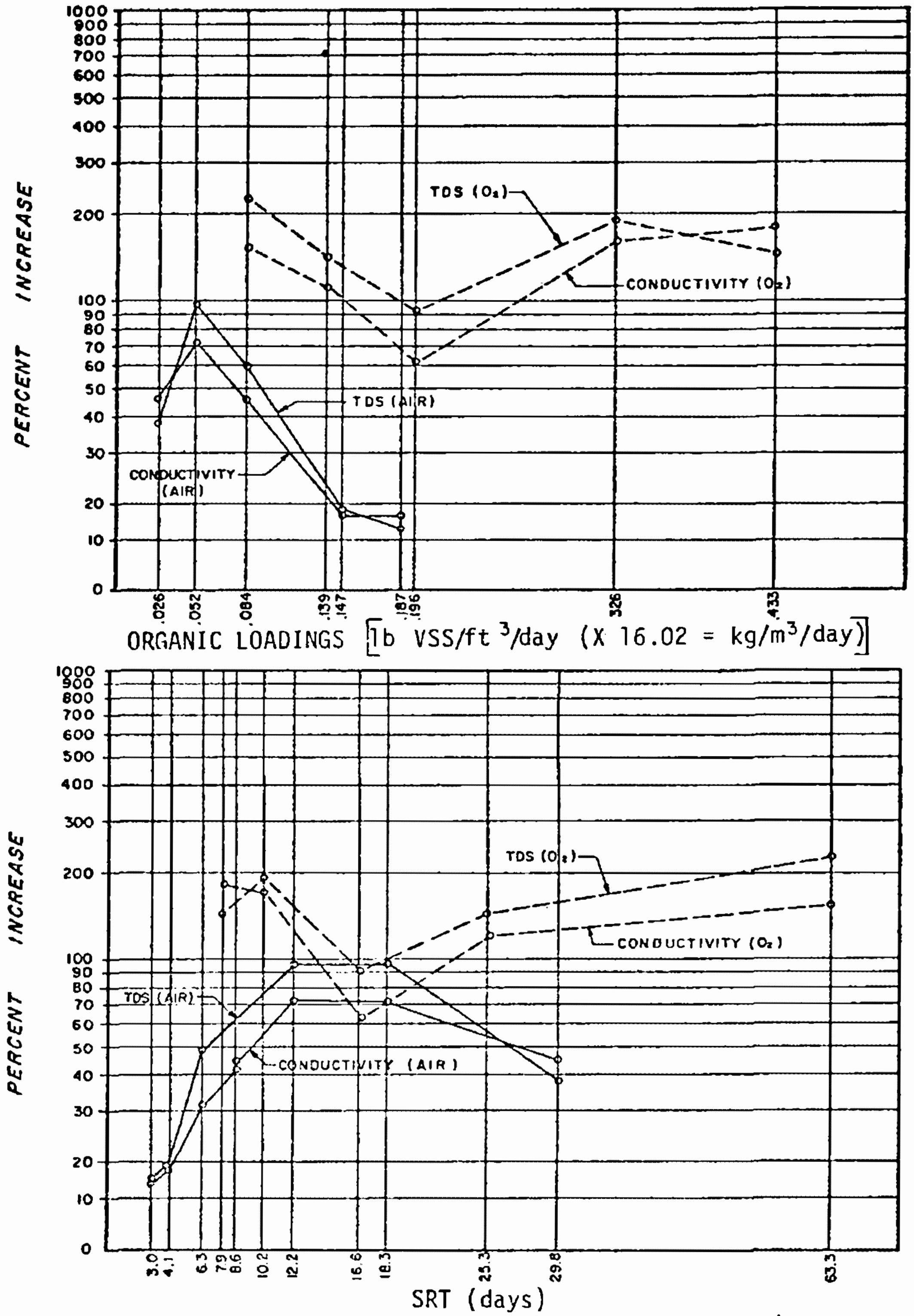


Fig. 54. Air versus oxygen performance-percent change in conductivity and TDS as a function of organic loadings and SRT

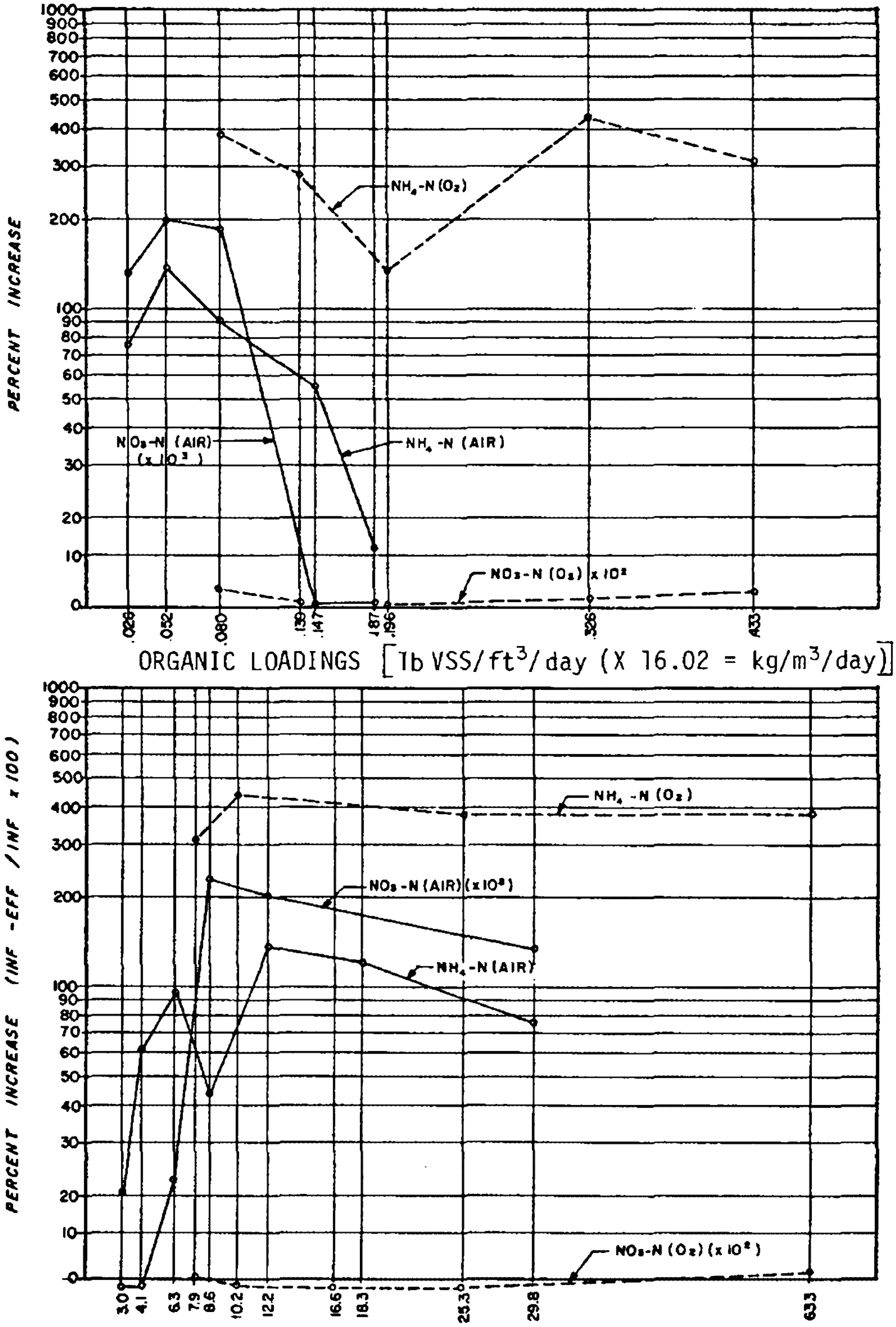


Fig. 55. Air versus oxygen performance - percent change in NH_4 and NO_3-N as a function of organic loadings and SRT

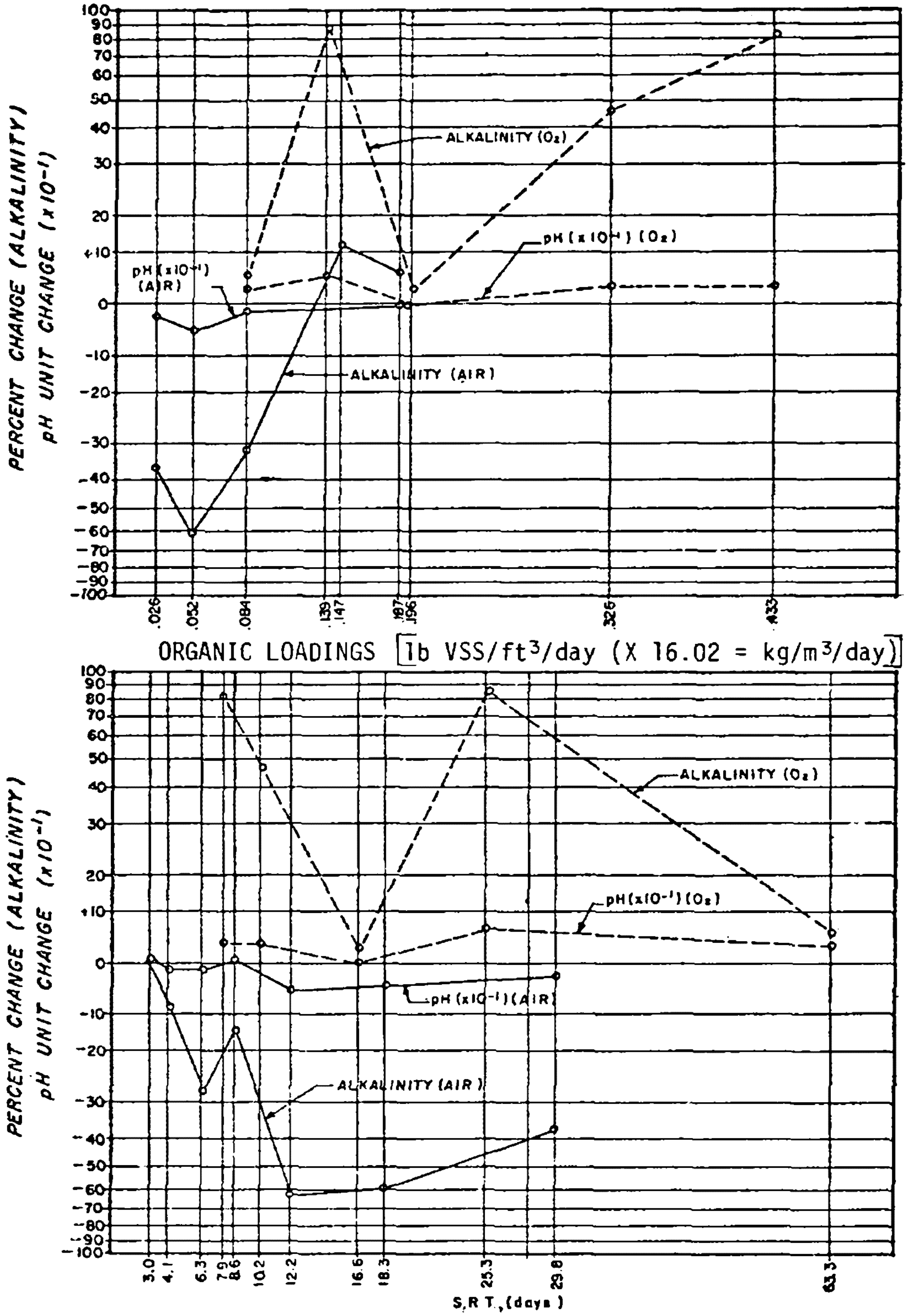


Fig. 56. Air versus oxygen performance - alkalinity and pH change as a function of organic loadings and SRT

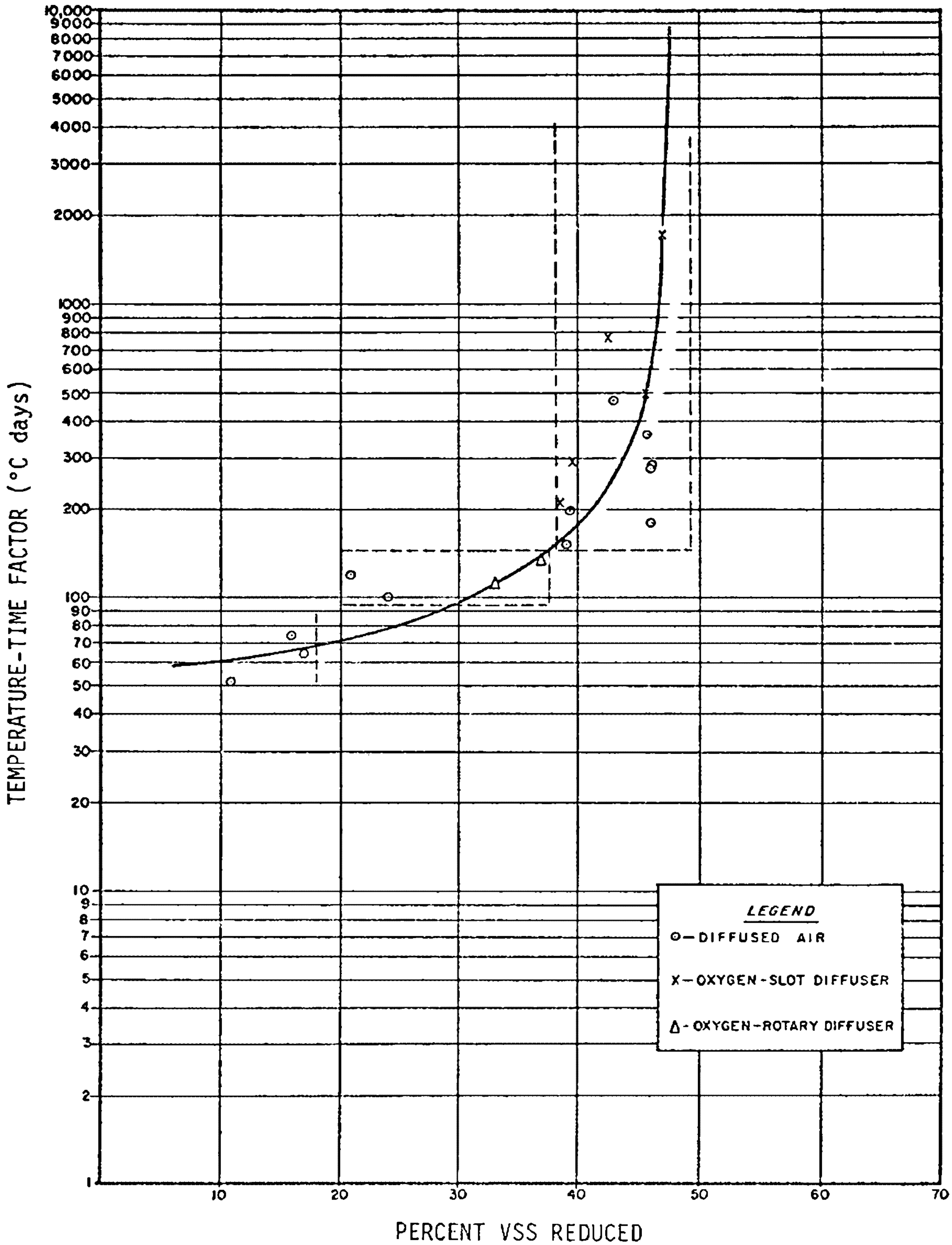


Fig. 57. Temperature-time factor versus percent VSS reduced in air and oxygen digesters

alkalinity, and pH were always greater in the effluent than the influent. Variability in pH and alkalinity changes were related to stripping of CO_2 and volatile organic acids. For the air digester, the best performance coincided with the highest rate of nitrification and highest pH and alkalinity differential between influent and effluent. The measurement of pH could be used in the air digester under conditions of nitrification as a good indicator of stability. In the oxygen digester nitrification did not occur and pH could not be used as an indicator of stabilization.

Figure 58 shows VSS reduction as a function of loading rates for both the oxygen and air digesters. At loading rates below 1.28 kg VSS/m^3/day (0.08 lb VSS/ft^3/day) the air system results were equal to or better than the oxygen digester. At loadings of 2.24 kg VSS/m^3/day (0.14 lb VSS/ft^3/day), the performance of the oxygen and air digesters were approximately equal. Above 2.24 kg VSS/m^3/day (0.14 lb VSS/ft^3/day) the performance of the air system declined rapidly, while the oxygen digester continued to perform well up to loading rates as high as 9.6 kg VSS/m^3/day (0.6 lb VSS/ft^3/day).

Figure 59 shows the oxygen utilization efficiency expressed as lb O_2 supplied per lb VSS reduced versus loading rates for all air and oxygen flow-through tests. The ranges of oxygen efficiency were related to the three different oxygen transfer systems used. The best performance with the diffused air system required 15 kg O_2 supplied/kg VSS reduced. The best performance using the pure oxygen FAD required 2.3 kg O_2 supplied/kg VSS reduced. The pure oxygen RAD required only 1.36 kg O_2 supplied/kg VSS reduced at its best performance. The optimal loading rate for high oxygen transfer efficiency was 1.28 kg VSS/m^3/day (0.08 lb VSS/ft^3/day) for the diffused air digester. The optimal loading range for the pure oxygen system was not determined, as the highest loading of 9.6 kg VSS/m^3/day (0.6 lb VSS/ft^3/day) did not cause system failure. The change in oxygen transfer efficiency in the diffused air digester varied with temperature and liquid depth, ranging between 5.2% and 19.3%. With the FAD, oxygen efficiencies as high as 93% were experienced in one of the batch tests. This efficiency could not be consistently maintained during the flow-through testing. With the substitution of the RAD for the FAD, oxygen transfer efficiencies in excess of 90% were consistently achieved for several months of continuous operation. In order to ensure high oxygen transfer efficiencies with an open tank oxygen digester, it is

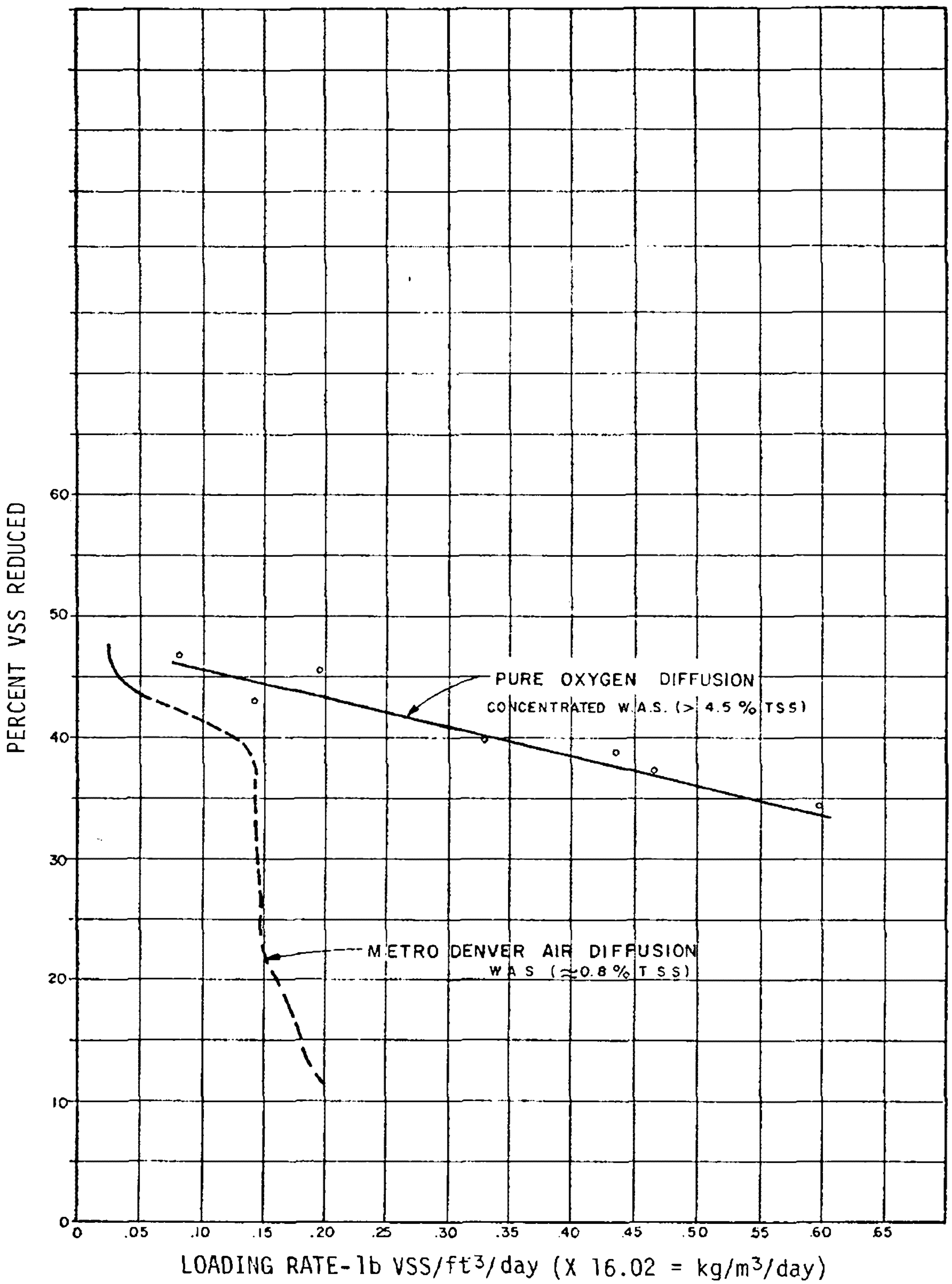


Fig. 58. Air versus oxygen performance-percent VSS reduction as a function of loading rate

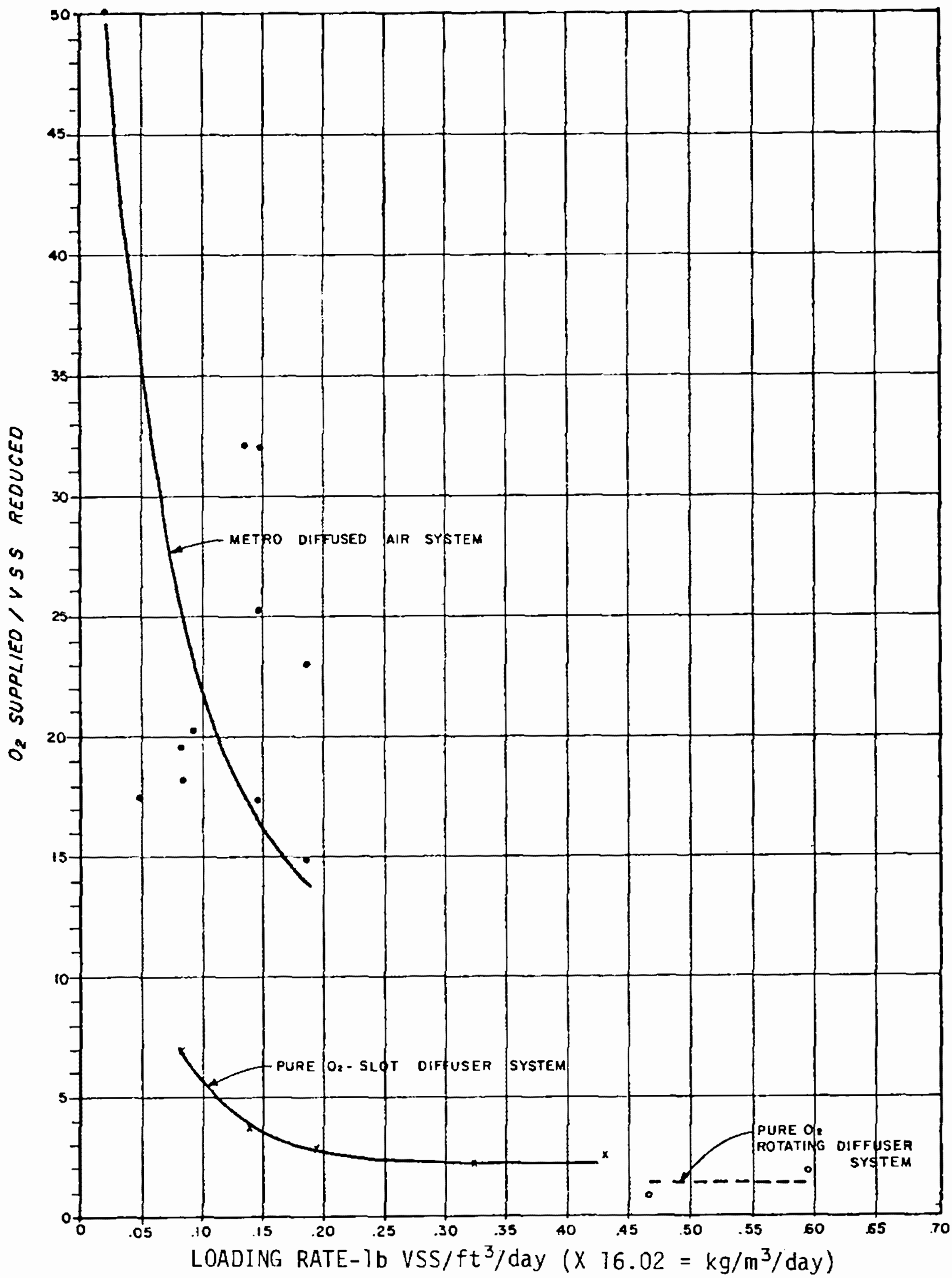


Fig. 59. Air versus oxygen performance-oxygen supplied/VSS reduced as a function of loading rate

necessary that the DO never exceed the saturation concentration at the air-liquid interface.

Comparison of the dewaterability of undigested and aerobically digested sludges from the diffused air and oxygen digesters indicated no significant differences in vacuum filter specific resistance ($r_s = 10^9$ sec^2 /gr) for SRT between 3 and 13 days. Differences in filter leaf performance tests were observed. Figure 60 indicated that for the air digester, dewaterability by vaccum filter comparing chemical costs with filter yields improved after aerobic digestion. For the oxygen digester a 50% increase in chemical costs was required in order to obtain equivalent vacuum filter performance with the digested sludge compared with undigested sludge. The chemical demand of the digested sludge from the air digester was approximately equivalent to that of the air floatation thickened WAS loaded to the oxygen digester. It appears that for dilute sludge ($<$ 1.0% TS), aerobic digestion improves vacuum filter performance by reducing the volatile fraction. After digestion of air flotation thickened WAS (4 to 5% TS), there is an adverse effect on vacuum filter performance which is related to the decrease in solids concentration. The effect of SRT in the digester on air flotation polymer demand for the diffused air system is directly related to sludge particle size and TSS/VSS ratio. The higher SRT in the digester results in higher polymer demand

Microscopic analysis of invertebrates revealed some interesting differences between the air and oxygen digesters. The air digester VSU ranged between 1.8 and 27.4 g/l, averaging 10.5 g/l. For the pure oxygen flow-through digester, the VSU in "A" tank averaged 13.8 g/l, compared with only 2.4 g/l in tank "B". The biomass loaded to the pure oxygen digester represented by tank "A" was approximately equivalent to the VSU results for the diffused air digester. The reduction in VSU observed in tank "B" represented equilibrium conditions in the pure oxygen digester. Ecological diversity, expressed as the number of different taxonomic groups appearing in any particular sample, was higher in the air digester than tank "A" of the oxygen digester. Diversity in "B" tank was lower than observed in tank "A". During the batch tests, invertebrate diversity declined with increasing detention time. The sludge loaded to the oxygen batch tests system had 3 to 4 out of 6 taxonomic groups initially, but the final sample after the 21 days SRT had 0 to 1 out of 6 taxonomic groups. Rotifers represented the major taxonomic group by weight and volume in the air digester with the

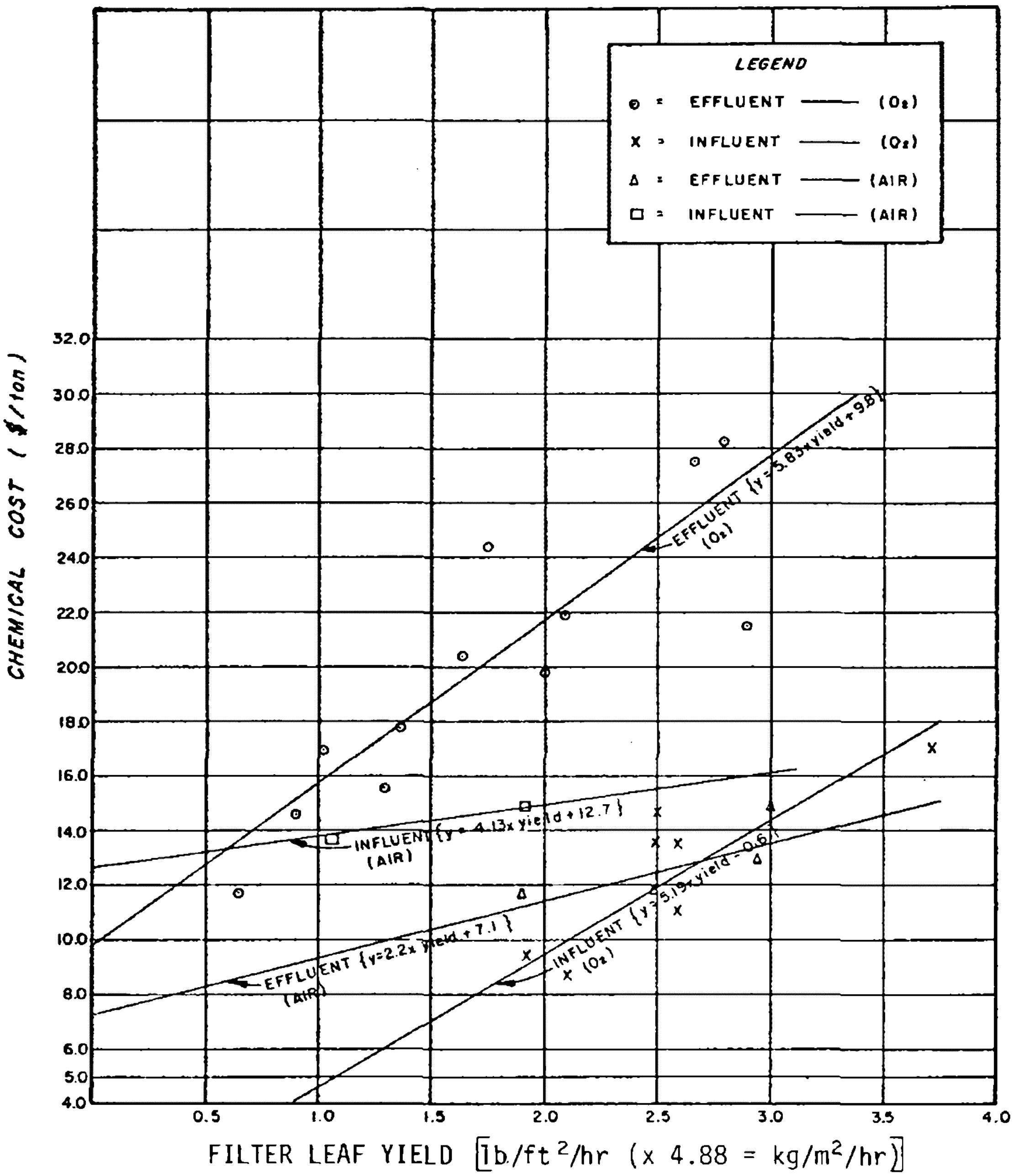


Fig. 60. Air versus oxygen performance-filter leaf yield per unit chemical cost

exception of shock loading or temperature periods. Rotifers were absent in all samples observed from "B" tank of the pure oxygen digester. Flagellates and ciliates comprised the majority of the invertebrate biomass in the oxygen digester. The total invertebrates as a percent of VSS ranged between 2.9% and 54.2% in the air digester, averaging 19.7%. In the pure oxygen digester, the total invertebrates as a percent of VSS ranged between 1.0 and 10.0% averaging 4.2% in "A" tank and 1.0% in "B" tank. The invertebrate population as a part of the total VSS biomass was reduced between the diffused air digester effluent and "A" tank of the oxygen system by 80%, and was further reduced by 77% between "A" tank and "B" tank. Temperature changes and loading stresses influenced population dynamics in the diffused air digester. It is assumed that the conditions of crowding and the high mixing energy in the pure oxygen digester created an environment which was inimical to growth and reproduction of higher invertebrate forms. In the pure oxygen digester, VSS reduction at high loadings and solids concentrations was dependent almost entirely upon mesophilic bacteria. In the air digester, the rotifer population had a significant correlation with VSS reduction +0.87. During the periods of optimal performance, rotifers made up as much as 50% of the dry weight biomass.

The concentration of ATP in the diffused air digester effluent averaged 0.34 mg/l compared with 0.65 to 1.2 mg/l in the effluent from the oxygen digester, using the tris buffer extraction method. The ratio of ATP/VSS was 58 x 10^6 in the air digester, and 18 to 31 x 10^6 for the oxygen digester (phases 5 and 6). The percent reduction of ATP was not measured in the air digester, but averaged 65% in the oxygen digester. The ratio of ATP/VSS reduced was quite uniform, averaging 1.8 for the pure oxygen digester. Fecal coliform reductions in the air digester ranged between 13.5% and 97.1% increasing with higher temperatures and lower loading rates. In the pure oxygen batch tests, fecal coliform reduction was directly related to detention time, reaching a maximum of 98.8% during batch test 1 (20 days SRT) versus 67.2% for batch test 2 (14 days SRT). The higher fecal coliform reductions in batch test 1 may also be related to the elevated temperatures experienced during that test.

The ecology of the pure oxygen digester was directly influenced by the crowding induced by the air flotation polymer conditioning of the biomass. Quaternary ammonium compounds which constitute the base of some of the cationic polymers used for dissolved air flotation may have caused a biostatic or biocidic toxicity effect expressed as a reduction in ecological diversity. The mixing energy required through the FAD to maintain the optimal oxygen bubble size was also inimical to growth and reproduction of the larger organisms such as rotifers that were observed to be predominant during the best performance periods in the diffused air digester.

BENEFIT - COST ANALYSIS

Figures 61 and 62 show the relationship between percent WAS in the total sludge mixture and sludge processing costs. The dramatic decrease from \$60 to \$40 per mil gal in sludge processing costs between 1970 and 1972 was directly attributable to reduction of WAS by aerobic digestion. The capital costs involved in this conversion were negligible. Since full scale aerobic digestion was initiated in July 1970, this upgrading modification has saved Metro Denver in excess of \$900,000 (Table 46). The major cost factor for diffused air digestion was electric power for compressed air. At a peak load cost of 7 mils/kwh, electric power costs \$1.98/mil liters/sec (\$4.20/mil cfd). Average air supply for the 13 month period was 4.3 mil liters/sec (9.1 x 10^6 cfd.) Aerobic digestion performance averaged 3.0 tons VSS reduced per day. Electric power costs for aerobic digestion averaged \$12.67 per ton of VSS reduced. Maintenance costs were very low involving primarily diffuser cleaning at an average cost of \$1.33 per ton for a total operation and maintenance cost of \$14 per ton. Prior to inauguration of aerobic digestion, WAS was disposed by air flotation, vacuum filtration and truck haul or incineration. The operation and maintenance costs of this alternative method averaged \$50 per ton. Aerobic digestion of WAS reduces the mass of sludge requiring further treatment and disposal. At an equivalent vacuum filter cost per dry ton of undigested and aerobically digested sludges, the savings as a result of digestion are \$50-\$14 = \$36/ton (1974 costs). The benefit-cost ratio of aerobic digestion compared with conventional sludge disposal methods is \$50/14 = 3.5. This economic comparison does not consider amoritization of capital equipment cost. In order to continue to obtain the benefits of VSS reduction resulting from aerobic digestion while utilizing the secondary capacity for its originally intended purpose, Metro staff is at present considering the conversion of an existing - 3755 m^3 (1 mil gal) holding tank to a pure oxygen digester utilizing RAD. Table 47 summarizes the estimated economic benefits to Metro of such a conversion. The cost estimates were based on the on-site cryogenic generation of pure oxygen at operation and maintenance cost of

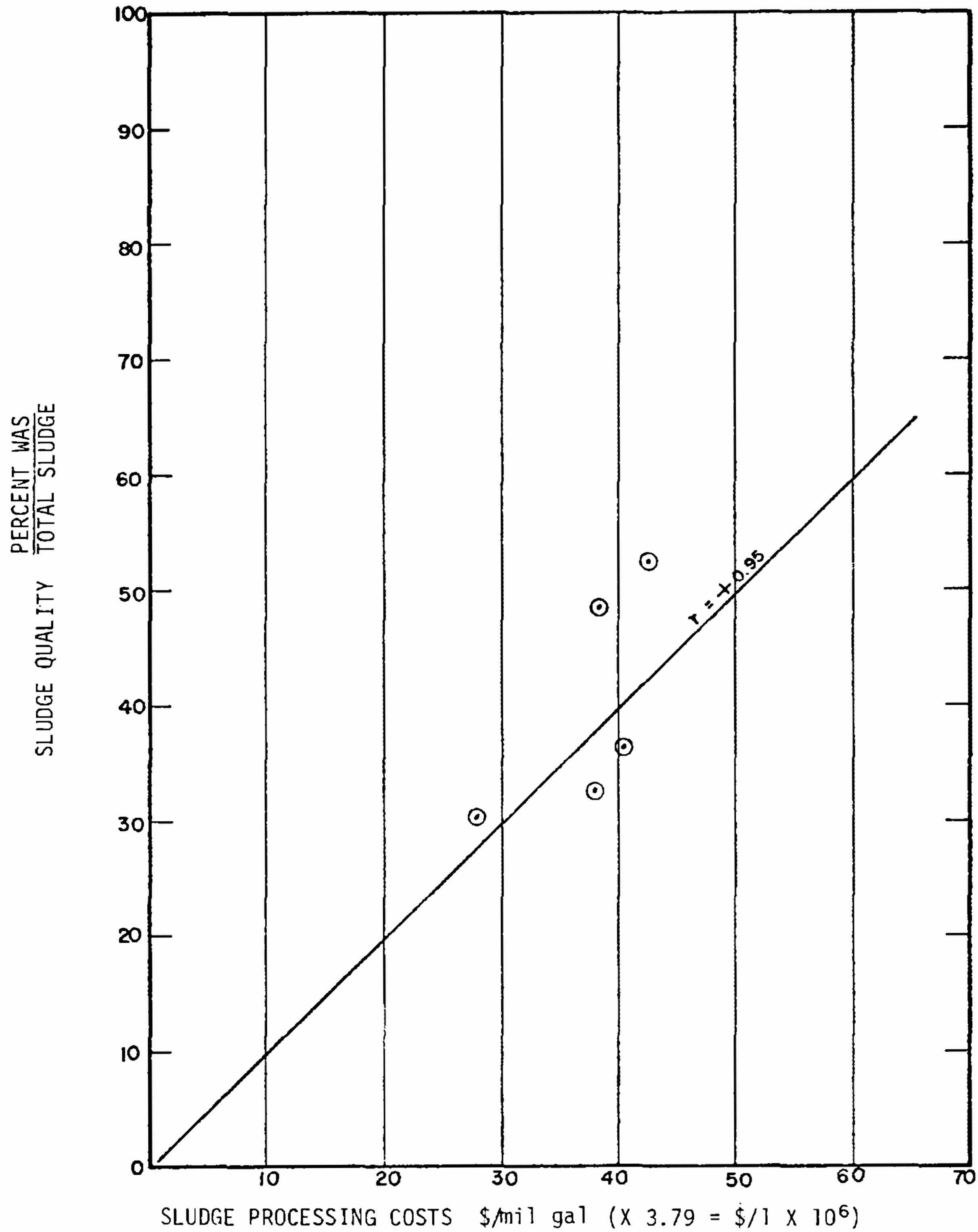


Fig. 61. Sludge processing cost as a function of sludge quality

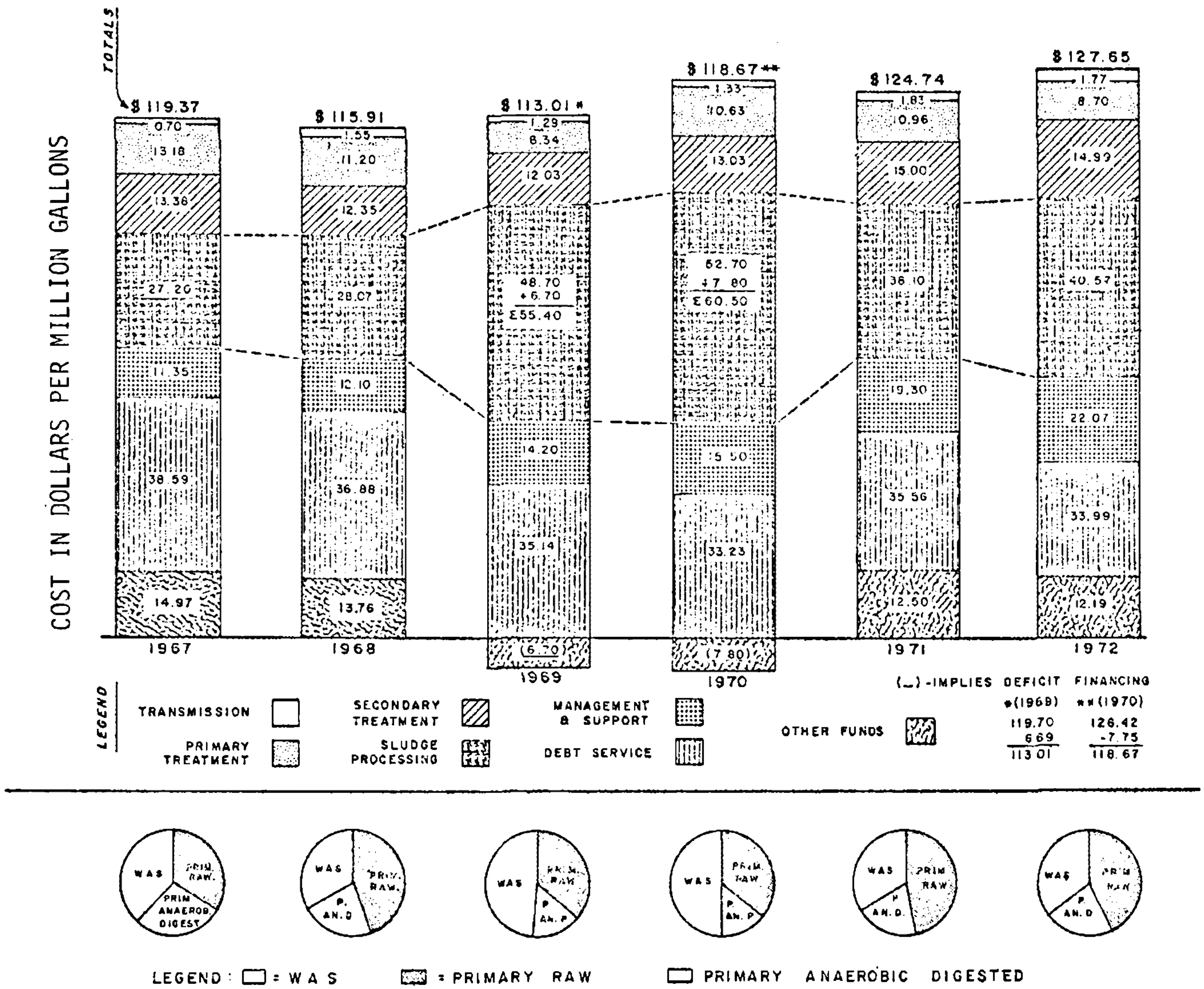


Fig. 62. Metro unit cost of sewage treatment versus time

Table 46. Cost savings of Metro diffused air aerobic digestion (1970-1974)

	1968	1969	1970	1971	1972	1973	1974
Total W A S Generated (X 1000 Tons)	6.5	17.9	19.9	13.0	15.3	17.2	19.3
Conc. W A S (X 1000 Tons)	6.5	17.9	17.4	9.3	10.2	12.5	14.7
WAS Reduced by Aerobic Digestion (X 1000 Tons)	0	0	2.5	3.7	5.1	4.7	4.6
Savings due to Aerobic Digestion (X $1000)			112	167	230	212	207
Total Cost Savings =		$928,000					

Table 47. Potential benefit of converting existing holding tank to pure oxygen aerobic digester

PARAMETER	UNITS	AEROBIC DIGESTION (@ 40% V S S Reduction)		
		* WITHOUT	** WITH	Δ
Sludge for Disposal	Tons/Yr (1)	38,975	31,730	7,245
Chemicals	Tons/Yr (1)	13,640	9,520	4,120
Sludge + Chemicals to Soil	Tons/Yr (1)	52,615	41,250	11,365
Cost ***	$/Yr	*2,340,000	**1,430,000	910,000

*Without Aerobic Digestion - Sludge Disposal Costs = $60/ton
**With Aerobic Digestion - Sludge Disposal Costs = $45/ton (assuming pure O_2 available @ $10/ton)
*** Costs do not include capital expenditure for conversion

(1) Tons/yr x 0.907 = metric tons/year

approximately $10 per ton. The capital cost of this conversion has been estimated to equal approximately 50% of the capital costs that would be required for building anaerobic digesters to handle an equivalent amount of WAS. Operating costs at a oxygen demand of 1.3 tons oxygen per ton VSS reduced would approximately equal $15 per ton. This cost is equivalent to the operating and maintenance costs anticipated for anaerobic digestion.

SYMBOLS AND ABBREVIATIONS

Aerob. - aerobic - in the presence of oxygen
AMP - Adenosine mono phosphate
Anaerob. - in the absence of oxygen
ATP - adenosine tri phosphate
AVG - arithmetic mean

BOD - biochemical oxygen demand
BVDS - biodegradable volatile dissolved solids
BVSS - biodegradable volatile suspended solids

^oC - degrees centrigrade
Calc. - calculated value
Cfm - cubic feet per minute
Cfd - cubic feet per day
Ci - concentration of settling sludge - g/l
CiVi - solids weighted settling velocity - g/cm^2 hr
COD - chemical oxygen demand
COD_{BO} - biodegradable chemical oxygen demand
Coli - coliform bacteria
Comp - composite sample
Conc. - concentration

DIG. - digested
DMSO - dimethyl sulfoxide
DNA - deoxy ribonucleic acid
DO - dissolved oxygen concentration
DS - dissolved solids

EFF - effluent waste from digester

FAD - fixed active diffuser
FDS - fixed dissolved solids
FS - fixed solids
FSS - fixed suspended solids
ft - foot
ft^3 - cubic foot

g - gram
gal - gallon
gpm - gallon per minute

hr - hour

INF - influent feed to digester
INV - inventory

JTU - Jackson turbidity units

k - aerobic digestion rate coefficient
K_{COD} - biodegradable COD rate coefficient - day $^{-1}$
K_{VSS} - biodegradable VSS rate coefficient - day $^{-1}$
K_r - specific oxygen uptake rate mg/hr/g VSS
K_t - reaction rate coefficient at temperature T^oC
K_{20} - reaction rate coefficient at 20^oC
kg - kilogram

l - liter
lb - pound

m - meter
m^3 - cubic meter
MAX - maximum
Metro - Metropolitan Denver Sewage Disposal District No. 1
mg - milligram
MGD - million gallons per day
mil - million
mil. gal. - million gallon
MIN - minimum
ml - milliliter

N - nitrogen
N.A. - data not available
NH_4-N - ammonium
No. - number
NO_3-N - nitrate

O_2 - pure oxygen gas
obsv. - observed
OUR - oxygen uptake rate mg/l/hr

pH - negative log of hydrogen ion concentration
PO_4 - phosphate
press. - pressure
psig - pounds per square inch of gauge pressure

R_r - oxygen uptake rate
r_s - specific resistance to vacuum filtration
RAD - rotating active diffuser
RED - reduced
RPH - revolutions per hour
RPM - revolutions per minute

S - concentration of biodegradable cell material
Sa·t - concentration-time factor-g·hr/l
sec - second of time
SRT - sludge retention time-days
STP - standard temperature and pressure - 20^oC and 760 mm
SVI - sludge volume index-ml per 30 min/g TSS

T - temperature
t - hydraulic detention time in digester
TDS - total dissolved solids
TKN - total Kjeldahl nitrogen (organic + ammonium)
TS - total solids
TSS - total suspended solids

Vi - settling velocity - cm/hr
VDS - volatile dissolved solids
vs - versus
VS - volatile solids
VSS - volatile suspended solids
VSU - volumetric standard units - ml/l

WAS - waste activated sludge

yd - yard
yd^3 - cubic yard

ZSV - zone settling velocity

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APPENDIX

VOLUMETRIC STANDARD UNITS (V.S.U.)
CONVERSION FACTORS

TAXONOMIC GROUP	DIMENSIONS (MICRONS)	SPHERICAL VOLUME (μ^3) = 0.5xCUBE		CONVERSION FACTOR
Flagellates				
Small	8 x 8 x 8	256	2.4 Avg	.256
Large	30 x 20 x 15	4500		4.5
Amoeba	30 x 20 x 40	12,000		12
Rotifer	1200 x 40 x 40	1,000,000		1,000
Nematodes	1000 x 15 x 15	100,000		100
Unidentified Motile Ciliates	Average of All Motile Ciliates			26
Unidentified Stalked Ciliates	Average of All Stalked Ciliates			54
Chilodonella	60 x 45 x 40	54,000		54
Acineta	40 x 40 x 40	32,000		32
Euplotes	70 x 50 x 40	70,000		70
Aspidisca	40 x 30 x 25	15,000		15
Lionotus				
Small	35 x 15 x 15	4000	10 Avg	4
Large	50 x 25 x 25	16,000		16
Suctoria	60 x 40 x 40	48,000		48
Vorticella	60 x 40 x 40	48,000		48
Opercularia	20 x 50 x 50	88,000		83

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/2-75-035		

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AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
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5. SUPPLEMENTARY NOTES

6. ABSTRACT

Metro Denver Sewage Disposal District No. 1 (Metro) in 1970 converted excess secondary aerators to aerobic digesters. The plant scale diffused air system was compared with a pilot scale open tank oxygen system using very fine bubble fixed and rotating diffusers. For the air system volatile suspended solids (VSS) reductions ranged between 11.2% and 47.2%. A significant correlation was observed between VSS reduction and detention time-temperature factor. Cold shock eliminated nitrification for a five month period. When invertebrates, particularly rotifers, comprised a significant fraction of the biomass, digestion was maximal. The pollutant concentration in the supernatant from the aerobic digester averaged 10% of that from an anaerobic digester. For the oxygen batch tests, biodegradable VSS digestion rate coefficient k averaged 0.27. No correlation was observed between DO concentration and VSS reduction rates. The temperature of the oxygen digested biomass increased with increased loadings. At loadings greater than 2.25 kg VSS/m^3/day (0.14 lb VSS/FT^3/day), oxygen performance was superior to the diffused air system. Loadings as high as 9.6 kg VSS/m^3/day (0.60 lb VSS/ft^3/day) were successfully employed with the rotating diffuser oxygen system. To continue the aerobic digestion economic benefits of reduced sludge disposal costs, Metro is considering conversion of a 3,785 cubic meter (1 million gallon) sludge holding tank to an oxygen digester.

7. KEY WORDS AND DOCUMENT ANALYSIS

DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Activated sludge process, *Aerobic processes, *Oxygenation, Respiration, Biochemical oxygen demand, Metabolism, Biomass, *Design criteria, High temperature tests, Hygiene, Thickening, Aerobic bacteria, Flotation, *Sludge digestion, Vacuum filtration	*Biodegradability, Water pollution control, Biodegradable solids destruction, Odor reduction, Pathogenic organisms elimination	13B

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