CONF-791072--5

MASTER

ENERGY CONSERVATION AND SCALE-UP STUDIES FOR A WASTEWATER TREATMENT SYSTEM BASED ON A FIXED-FILM, ANAEROBIC BIOREACTOR*

R. K. Genung and W. W. Pitt, Jr.
Chemical Technology Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

and

G. M. Davis and J. H. Koon
Associated Water and Air Resources Engineers, Inc.
P. O. Box 40284
Nashville, Tennessee 37204

To be presented at the Second Symposium on Biotechnology in Energy Production and Conservation to be held in Gatlinburg, Tennessee, October 2-5, 1979.

*Research sponsored by the Division of Buildings and Community Systems, U.S. Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

DISCLAIMER

ENERGY CONSERVATION AND SCALE-UP STUDIES FOR A WASTEWATER TREATMENT SYSTEM BASED ON A FIXED-FILM, ANAEROBIC BIOREACTOR

SUMMARY

Oak Ridge National Laboratory (ORNL) is developing an energy-conserving wastewater treatment system based on a fixed-film anaerobic bioreactor. The treatment process is based on passing wastewaters upward through the bioreactor for continuous treatment by gravitational settling, biophysical filtration, and biological decomposition. A 2-year pilot plant project using a bioreactor designed to treat 5000 gallons per day (gpd) has been conducted using raw wastewater on a municipal site in Oak Ridge, Tennessee. Data obtained for the performance of the bioreactor during this project have been analyzed by ORNL and Associated Water and Air Resources Engineers (AWARE), Inc., of Nashville, Tennessee. From these analyses it was estimated that hydraulic loading rates of 0.2 gpm/ft^2 and hydraulic residence times of 10 hr could be used in designing such bioreactors for the secondary treatment of municipal wastewaters.

Conceptual designs for total treatment systems processing up to 1.0 million gallons of wastewater per day (mgd of wastewater) were developed based on the performance of the pilot-plant bioreactor. These systems were compared to activated sludge treatment systems also operating under secondary treatment requirements and were found to consume as little as 30% of the energy required by the activated sludge systems. The economic advantages of the process result from the elimination of operating energy requirements associated with the aeration of aerobic-based processes and with the significant decrease of sludge-handling costs required with conventional activated-sludge treatment systems. Methane produced by

anaerobic fermentation processes occurring during the biological decomposition of carbonaceous wastes also represented a significant and recoverable energy production term as wastewater flow rates approached 1.0 mgd.

To support its goal of commercializing the process, ORNL is presently engaged in developing a 50,000-gpd wastewater treatment system based on the conceptual designs developed by ORNL and AWARE. This project will probably be conducted jointly with the city of Knoxville, Tennessee, both for demonstration purposes and for continuing research and development with the process.

BACKGROUND

A pilot-plant wastewater treatment system based on a fixed-film, anaerobic bioreactor was designed during the summer of 1976 as a joint venture between ORNL and the Norton Company (Akron, Ohio). It was installed with the cooperation of the city of Oak Ridge in the late fall of 1976, and operated by ORNL for 2 years. The primary motivation for this joint effort was the development of a new technology with could reduce the increases in costs and energy consumption required by the passage in 1972 of Public Law 92-500 (and by PL 92-500 as amended by the Clean Water Act of 1977). Other background for this development and early performance data for the process were previously reported (1-2).

To enhance the transfer of technology to the private sector, ORNL engaged in a competitive bidding process to involve a consulting firm specializing in wastewater treatment in the evaluation of this new technology. As a result of this process, AWARE participated in analyses of the pilot-plant data and subsequently developed conceptual designs for total treatment systems based on the performance of the pilot-plant bioreactor. AWARE also provided estimates of the costs and energy requirements for these systems.

DESCRIPTION OF PILOT PLANT

The pilot plant was based on an anaerobic, fixed-film bioreactor (referred to by the acronym ANFLOW for its anaerobic, upflow operation) as shown in the flowsheet in Fig. 1. The bioreactor, a cylindrical tank constructed of fiberglass, was 5 ft in diameter and 18.3 ft high; it contained 10 ft of packing (200 ft^3), which consisted of 1-in. ceramic Raschig rings. Both the bioreactor and the packing were supplied by the Norton Company. The bottom of the column was a 45° cone with a flanged outlet; a 4-in gate valve was installed on the cone flange. Nozzles for feed inlet and gas outlet extended through the tank wall. The column was surrounded by 4 in. of insulation; all external piping was insulated with electrical traces. There were thermocouple taps near the top and bottom of the packed section, and a U-tube manometer tap at the top. An overflow weir and a collection trough in the top of the column were designed to remove effluent from the center of the tank.

A raw sewage stream entering the Oak Ridge East Treatment Plant was sampled immediately downstream of a comminuting pump used in the headworks of the city plant. A constant flow rate pump was used in conjunction with a flow-control valve, with the bypass from the valve being returned to the main sewage flume via an overflow box used for sampling purposes. Feed was pumped to a height above the column outlet and allowed to pass through the column by gravity flow; a hydraulic

ORNL DWG 79-18288

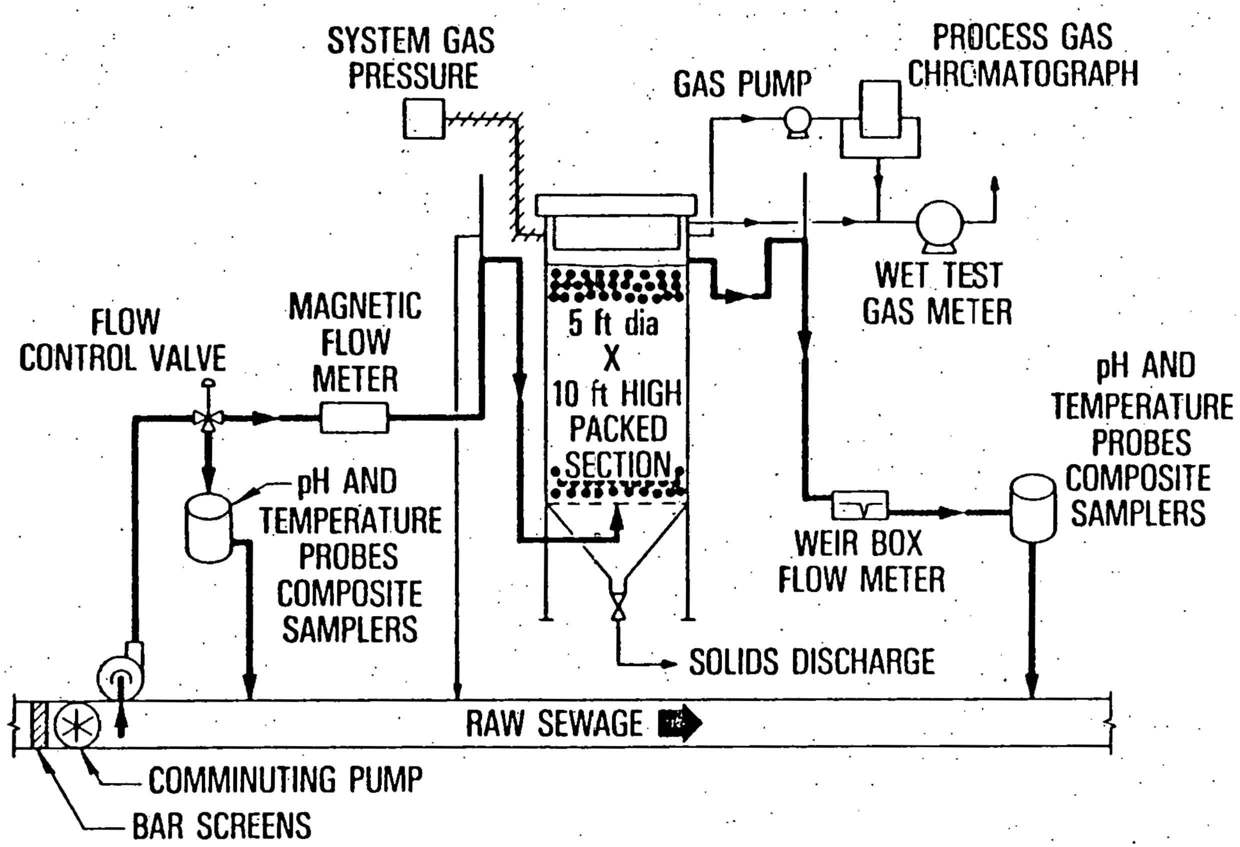

Fig. 1. ANFLOW pilot-plant flowsheet.

head of 2 to 4 in. was adequate to produce this flow. A liquid seal in the outlet line prevented ambient gas from entering the column through the effluent-return vent line. A final overflow box was used for sampling before the effluent was returned to the main sewage flume. The off-gas from the column was sampled and analyzed by an on-line gas chromatograph; the total off-gas volume was measured by a wet-test meter.

Continuous monitoring of pH and temperature was accomplished with on-line probes placed in the overflow boxes before and after the bioreactor. These boxes also contained pneumatic samplers for the collection of composite samples which were analyzed to evaluate the bioreactor's performance in wastewater treatment.

START-UP PROCEDURES

The packing material provided by the Norton Company was installed in the ANFLOW column by Norton with assistance from ORNL. The column was dry packed to enhance absorption of microorganisms, introduced later in the inoculum. The packed bed was heated and dried by blowing heated air through it until the packing reached a temperature of 40°C. A mixture of rumen fluid and anaerobic digestor sludge was then used to fill the column. A synthetic feed of sugars, volatile acids, and mineral salts was added to this inoculum to give an initial organic carbon concentration of approximately 800 ppm. The ANFLOW column was then allowed to cool for 1 week, after which the column temperature was approximately equal to the 18°C of the sewage on the Oak Ridge site at that time. During the cooling period, raw sewage was batch fed to the column in volumes of approximately 30 gpd. Continuous sewage feed at 1100 gpd was started in November 1976.

OPERATION AND PERFORMANCE SUMMARY

Feed Flow Rates

The pilot plant was designed to treat a nominal flow rate of 5000 gpd; as shown in Fig. 2, feed flow rates ranging from 1000 to 7000 gpd were actually used to investigate the bioreactor's response to a range of hydraulic loading rates (HLRs). Notably, the HLR corresponding to a feed flow rate of 7000 gpd at the pilot plant is approximatley 0.25 gpm/ft^2. Feed flow rates were maintained at constant levels for extended periods to evaluate bioreactor performance under steady-state conditions. Effects of diurnal variations in flow rates were briefly examined with no noticeable effect on bioreactor performance observed. These investigations will be continued in future work.

Temperature, pH, and Gas Production

The temperature and pH levels of the wastewater fed to the bioreactor are summarized using monthly averages in histograms in Figs. 3 and 4. Temperature variations followed seasonal cycles and ranged from 10 to 25°C. Column effluent temperatures closely followed the temperatures of the raw sewage except for the period of January through April 1977, during which a contingency preheater was used to prevent feed from freezing in external pipelines. This practice was discontinued after early problems with clogging of the flow-control valve were eliminated.

Neither feed nor effluent pH levels differed significantly from the value of 7 during the project. As would be expected, the production of volatile acids by the anaerobic digestion processes in the bioreactor caused effluent pH values to be measurably lower than feed values. In colder months, these acids were not efficiently converted to methane and tended to be discharged with the effluent, thus causing greater pH

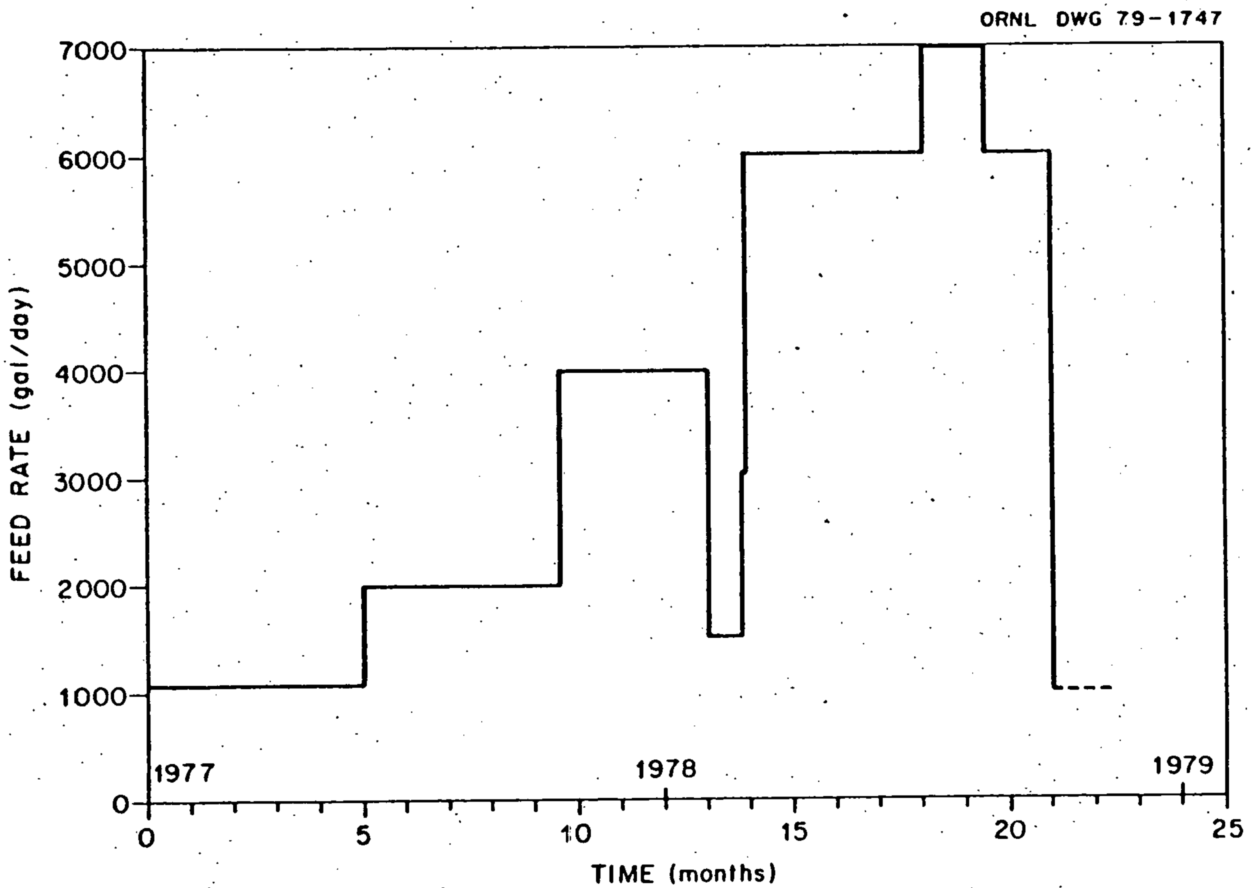

Fig. 2. Feed rate histogram for ANFLOW bioreactor.

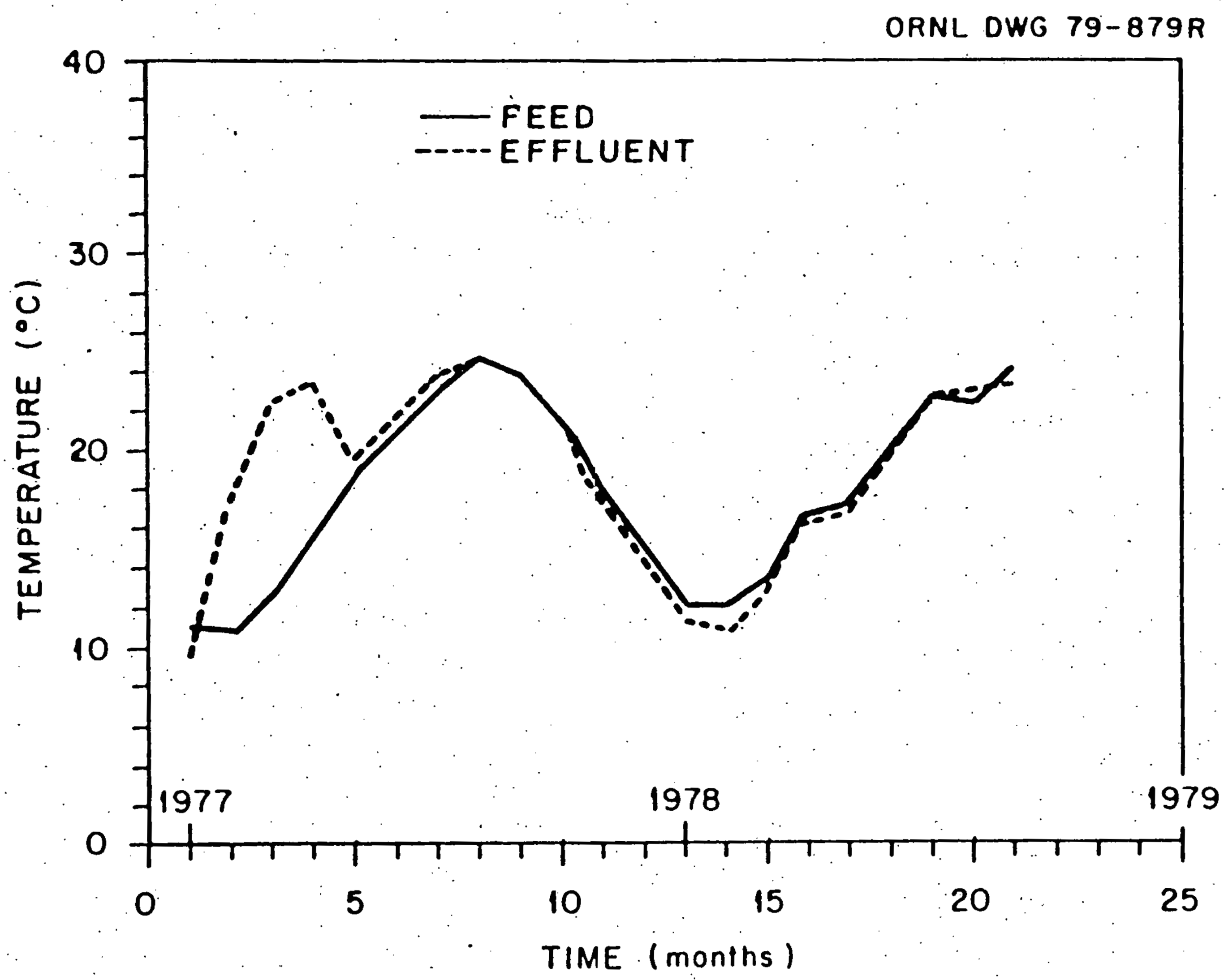

Fig. 3. Temperature histogram for ANFLOW bioreactor.

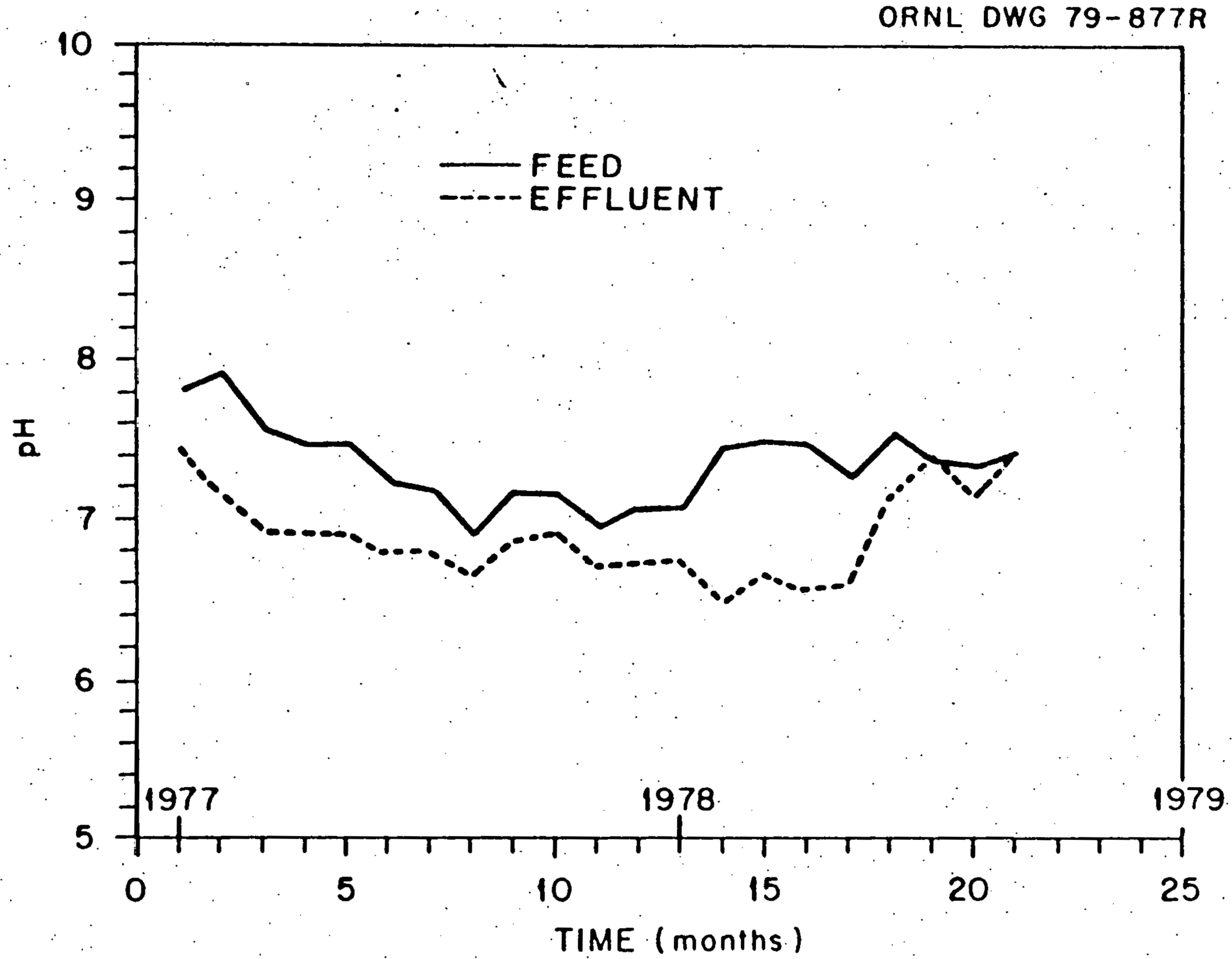

Fig. 4. pH histogram for ANFLOW bioreactor.

differences between feed and effluent during these months than in warmer months.

On several occasions, there were pH disturbances (probably associated with discharges of upstream metal-plating industries) in the feed lasting as long as 8 hr during which pH levels reached lows of 3 and highs of 10; these disturbances were dampened by the column and were observed to alter effluent levels by less than 0.5 pH units. One hypothesis proposed to partially explain the bioreactors resistance to these disturbances is that outer layers of the films attached to the packing absorbed the pH insults, possibly sloughing off as sludge for future removal and leaving protected film layers behind as a regeneration mechanism for the bioreactor.

Gas production rates measured during the project are summarized in Fig. 5; these rates reached monthly averages exceeding 100 liters/day. Methane concentrations in the bioreactor off-gas reached highs of 80%, as shown in Fig. 6. The remainder of the off-gas consisted of carbon dioxide and nitrogen. The methane produced was approximately 33% of that which could theoretically have been produced as calculated from measurements of the organic carbon removed from the wastewater by processes in the bioreactor. This efficiency was difficult to estimate, however, since carbon was removed by many mechanisms, some involving solubilization phenomena, for instance, which occurred over undefined periods.

Production rates followed the seasonal variations described for temperature, increasing as expected in the warmer months. The methane concentrations also increased in warmer months, thus following a pattern predicted by the decrease in volatile acids accumulation discussed earlier for these months.

ORNL-DWG 79-876

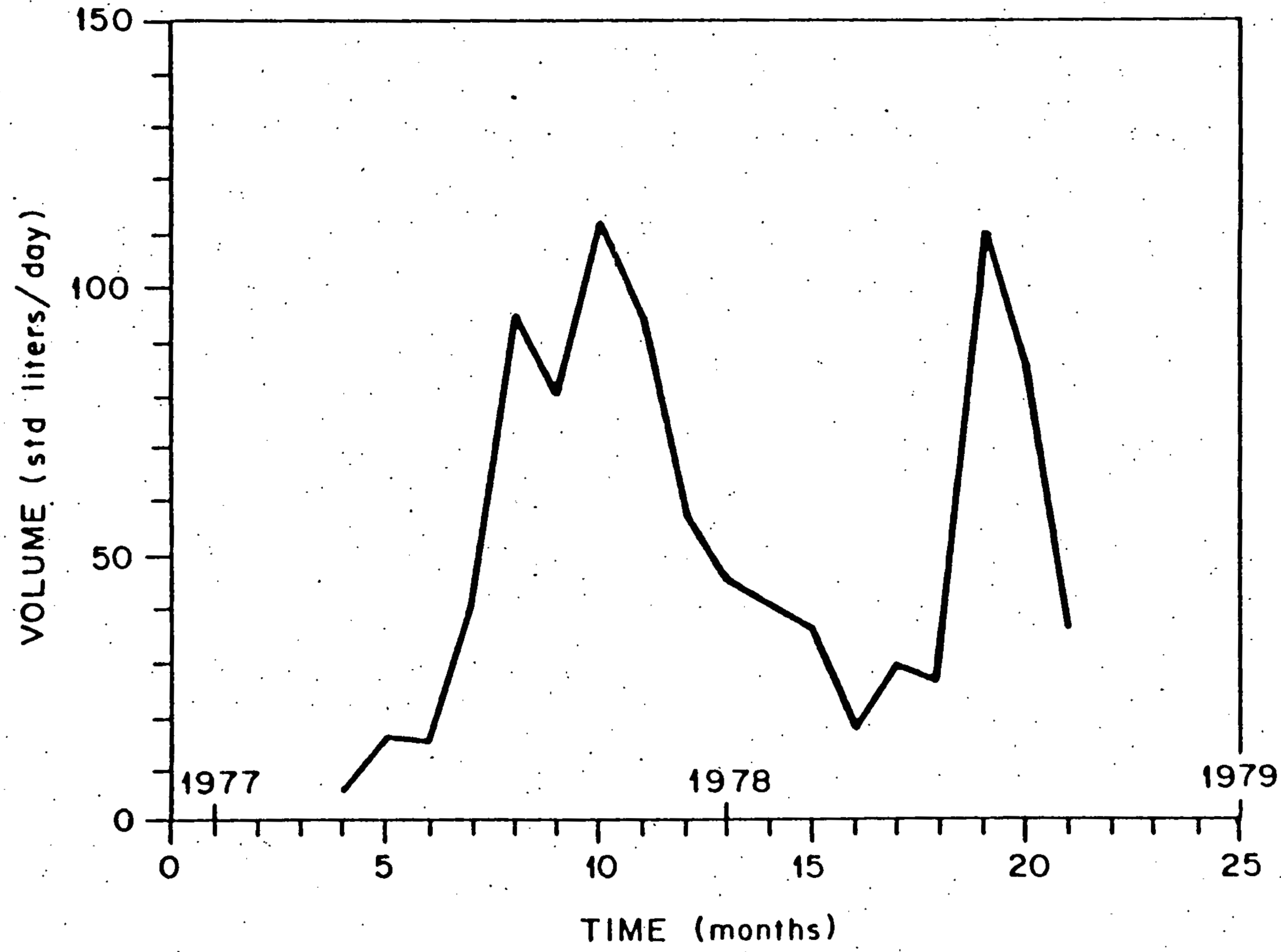

Fig. 5. Gas production by ANFLOW bioreactor.

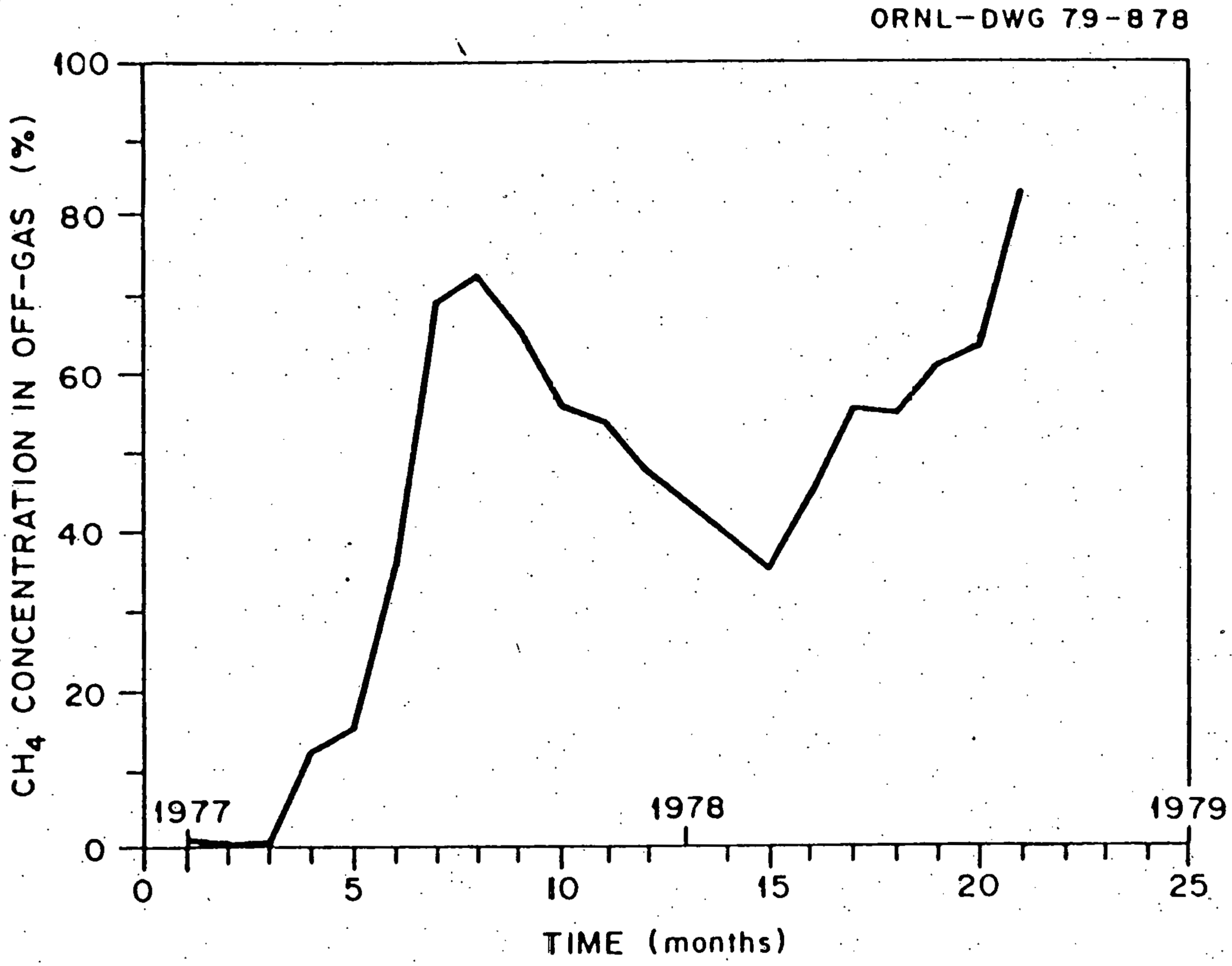

Fig. 6. Methane content of gas produced by ANFLOW bioreactor.

Removal of Suspended Solids

The levels of total suspended solids (TSS) in the feed varied significantly, reaching a maximum monthly average of 250 ppm as seen in Fig. 7. TSS levels in the effluent were generally below 30 ppm until the later months of the project. During this period, TSS levels in the feed reached the maximum observed and feed flow rates 20 to 40% above the 5000-gpd design flow rate were used. More importantly, the system had been operated for 15 months without removing nondigesting or slowly digesting solids from the bioreactor. In an optimized operation, the bioreactor would be periodically backwashed to remove such solids and to prevent or minimize their discharge in the effluent.

Figure 8 summarizes the effects of feed flow rate and TSS loading rate on the TSS removal rate obtained with the pilot-plant bioreactor. At design flow rates or less, an average TSS removal rate of 75% of TSS loading was obtained for loading rates as high as 55 lb TSS/day/1000 ft^3 of reactor, as can be seen. However, the bioreactor could not effectively remove TSS at loading rates as low as 25 lb TSS/day/1000 ft^3 of reactor when flow rates approached 7000 gpd. From these results it was postulated that a "sludge blanket" was formed in the bioreactor as solids accumulated, and that this sludge blanket could only be retained in the column by gradually reducing the HLR. It was apparent that periodic removal of solids from the bioreactor would be required if the bioreactor was to be operated continuously at a high HLR, and that the requirement for solids removal would be indicated by the usable HLR decreasing below an allowable limit. The operating cycle would thus be determined by the rate of solids accumulation in the bioreactor under given operating conditions.

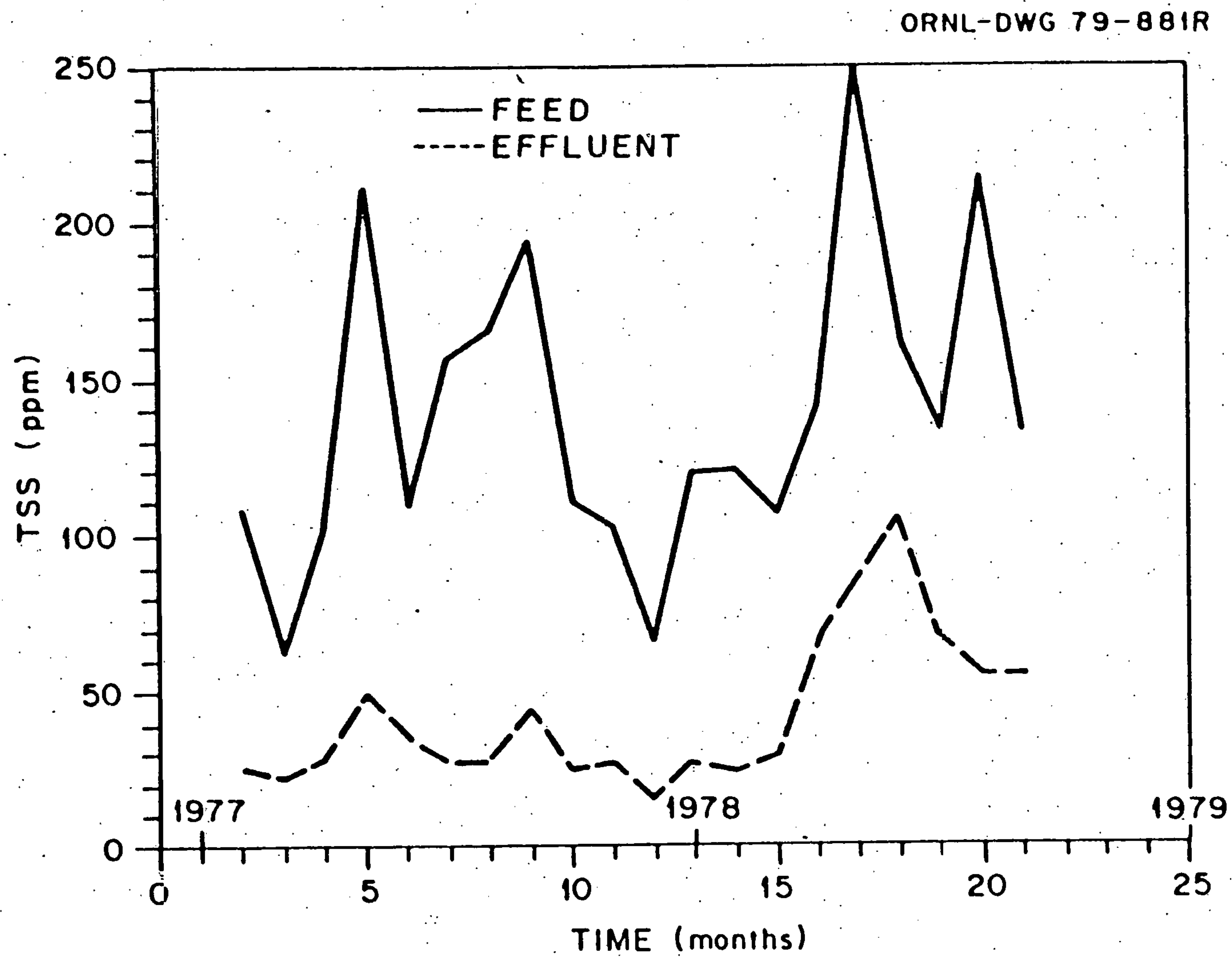

Fig. 7. Solids removal by ANFLOW bioreactor.

ORNL DWG 79-904

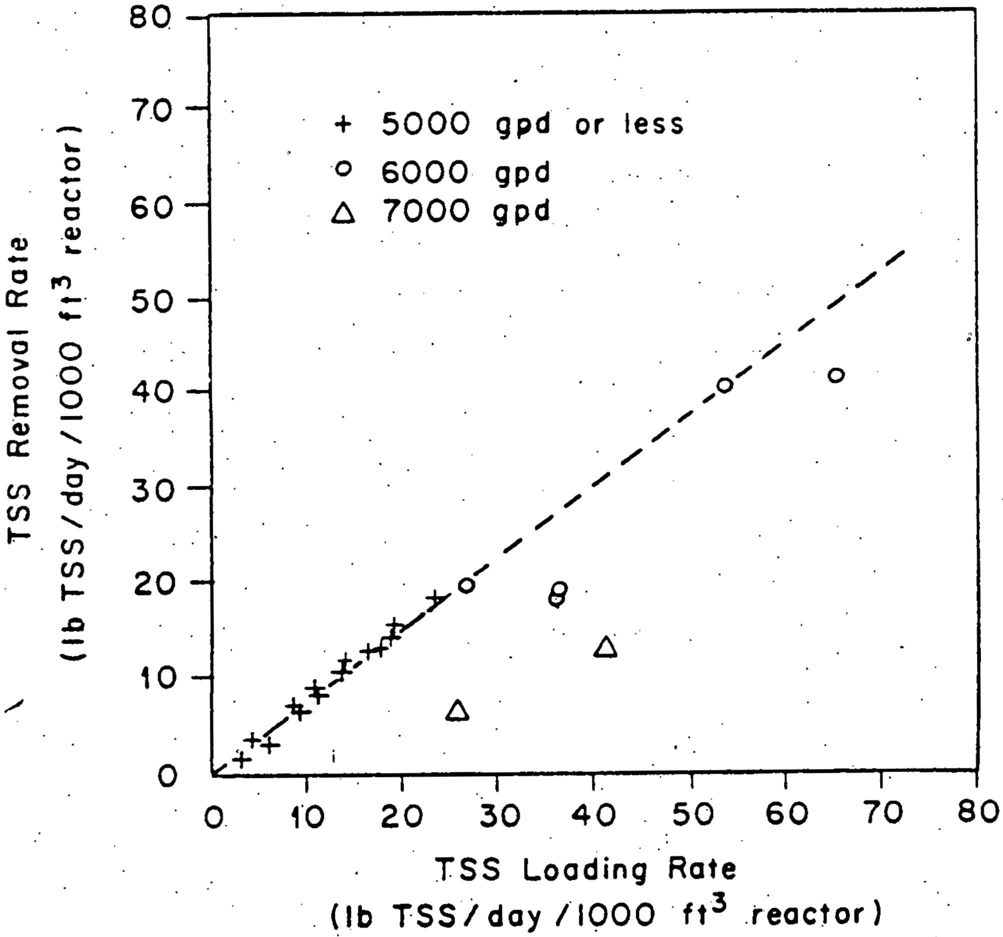

Fig. 8. Solids removal in ANFLOW bioreactor.

The bioreactor was drained by gravity-flow and washed with wastewater fed at 8000 gpd for 24 hr in order to test the feasibility of periodically removing solids. TSS removal rates were then re-evaluated at flow rates of 1000, 5000, and 7000 gpd.

Results are presented in Fig. 9 which shows that after solids removal, flow rates as high as 7000 gpd could be used while obtaining 75% removal of TSS. As shown in Fig. 8, this level of performance was previously limited to flow rates of 5000 gpd or less. Since the draining and washing did not remove films which were firmly attached to the packing, there was no problem in re-starting the bioreactor.

Removal of Biological Oxygen Demand (BOD)

Levels of 5-day biological oxygen demand (BOD) measured in the feed and effluent streams are summarized in Fig. 10 as monthly averages. Levels of BOD in the feed reached monthly averages as high as 220 ppm. Effluent BOD levels followed trends in the feed and ranged from 30 to 90 ppm. Since much of the BOD in the effluent was associated with TSS, increased efficiency in TSS removal, as discussed in the preceding section, would result in significant improvement in BOD removal.

As seen in Fig. 11, BOD removal rates could be correlated with BOD loading rates. These data show an average BOD removal of 55% in the column as operated during the pilot-plant project. During March 1978, the feed rate to the column was increased to 6000 gpd, 20% above the design value. As seen in Fig. 11, the column required an acclimation period but returned to the 55% removal rate in the following months. It is currently postulated that during the acclimation period, the column reached a new steady state with respect to the solids it could retain in the sludge blanket described earlier.

ORNL DWG 79-905R

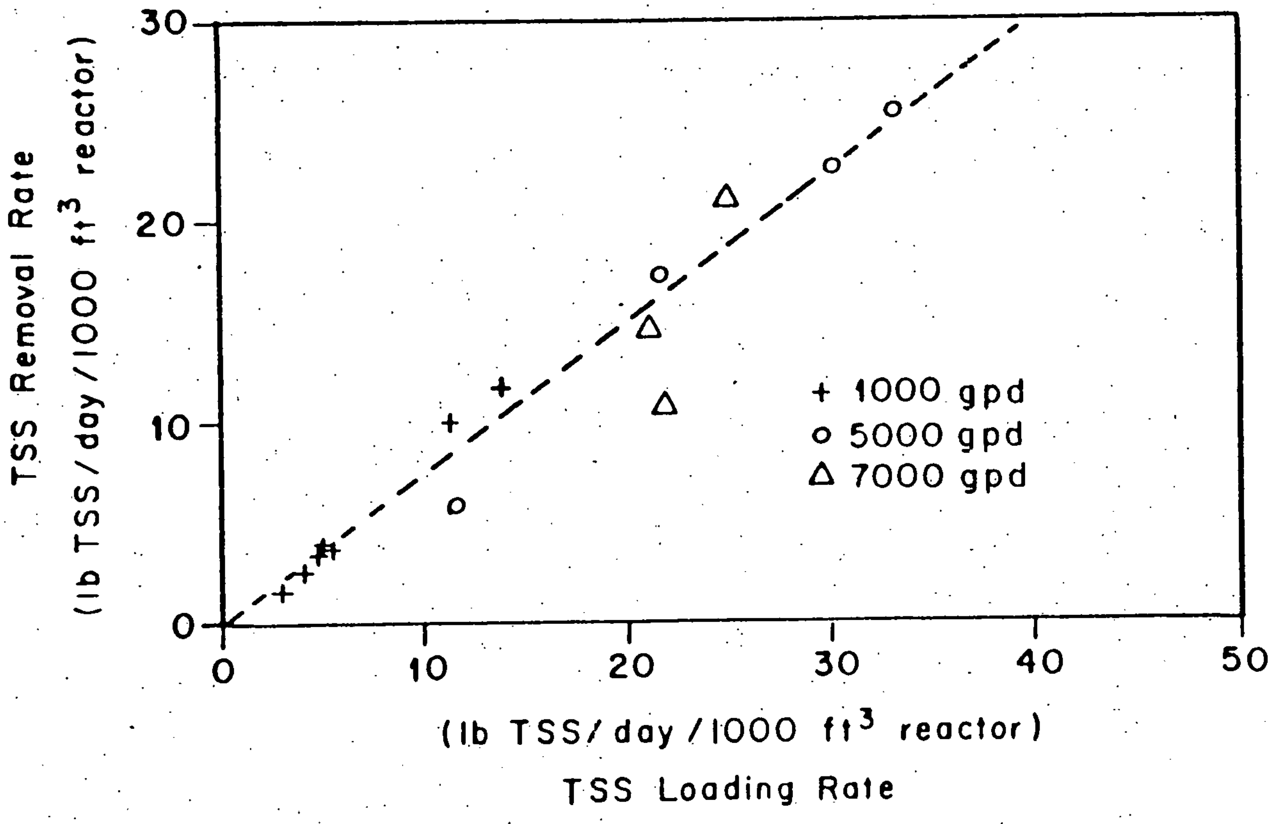

Fig. 9. TSS removal by ANFLOW column after draining and start-up.

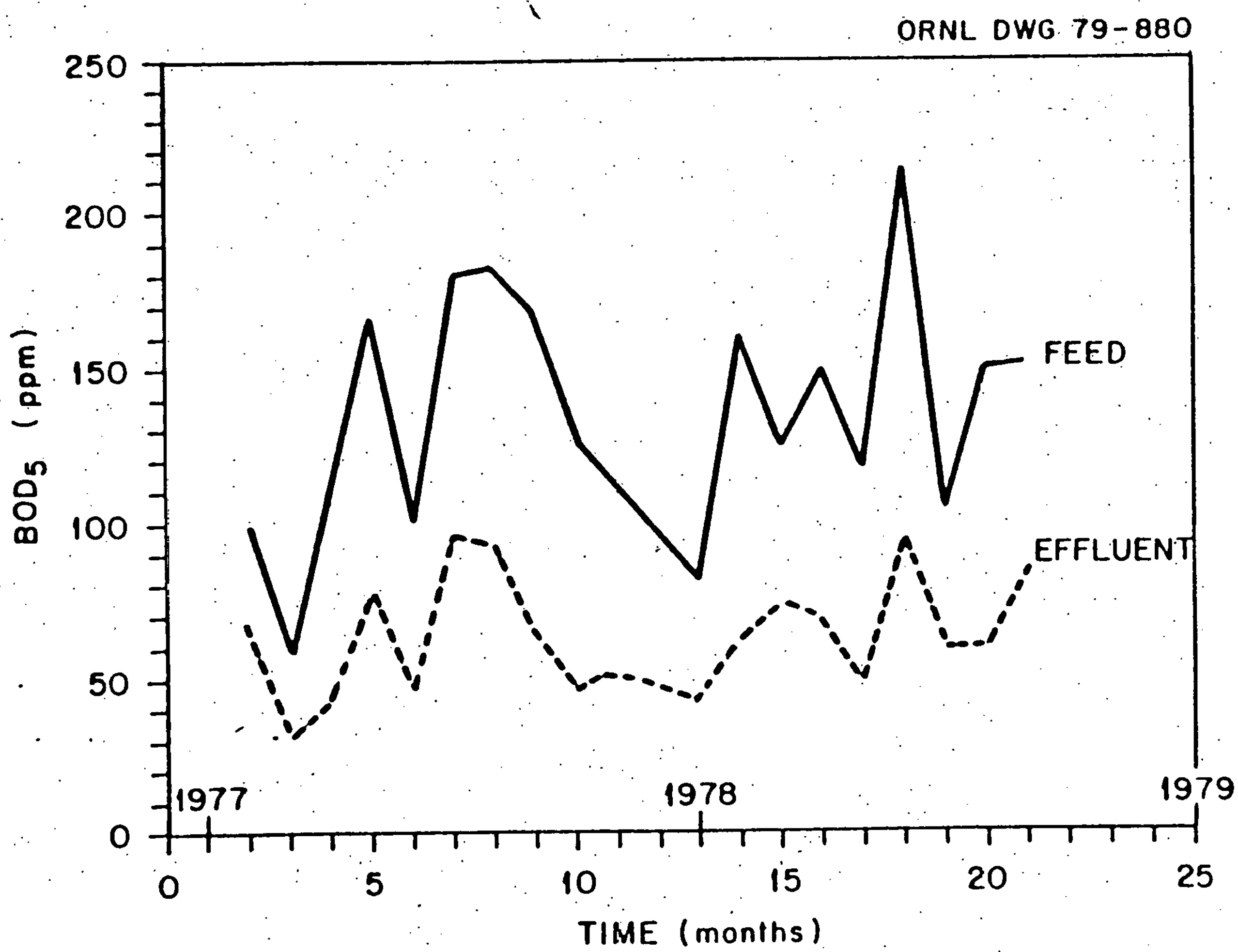

Fig. 10. Biological oxygen demand histogram for ANFLOW bioreactor.

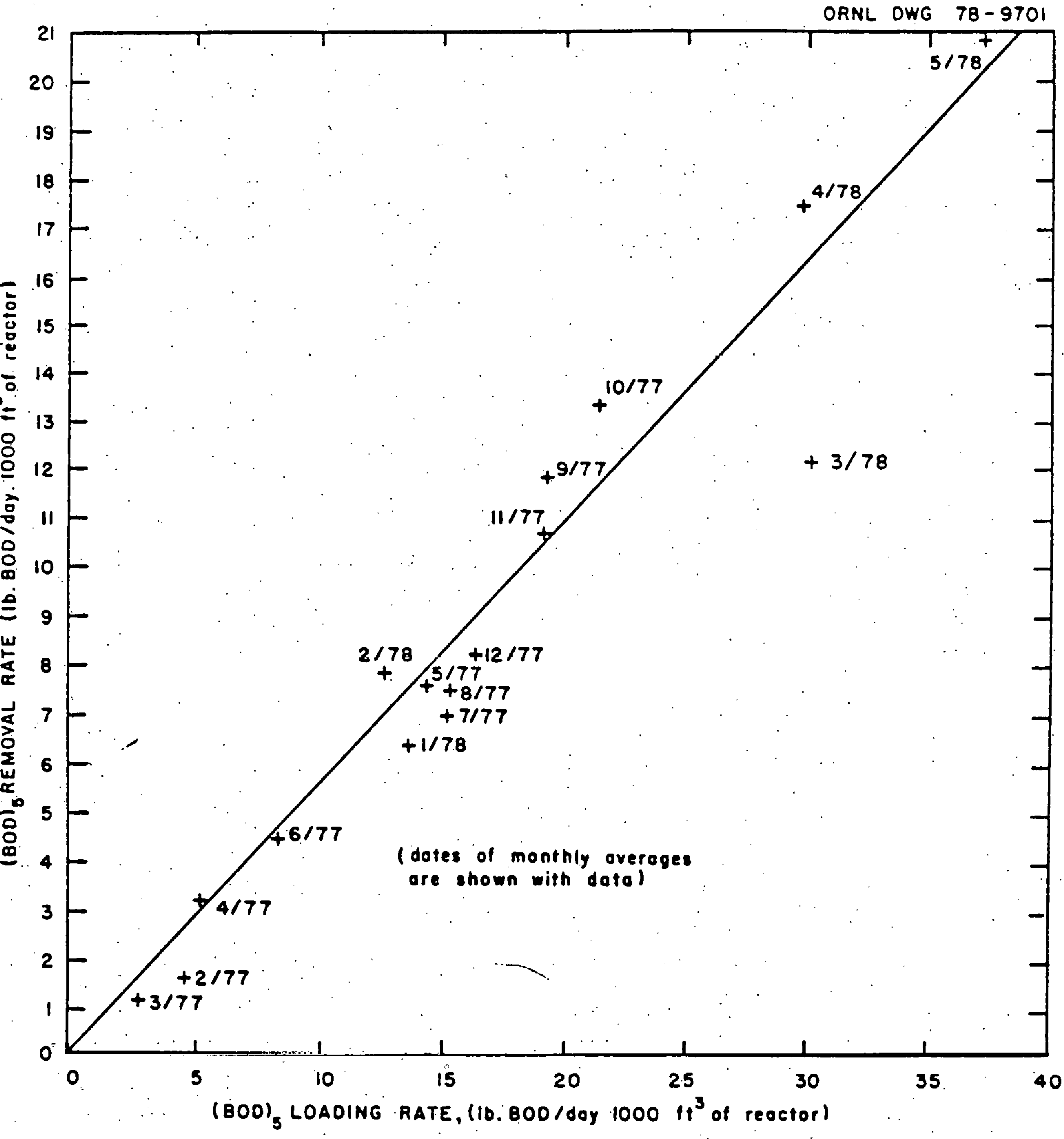

Fig. 11. BOD_5 removal rates at the ANFLOW pilot plant.

The midrange loading data shown in Fig. 11 were used to obtain a correlation of the averaged removal rates with the averaged operating temperatures during the corresponding months. As seen in Fig. 12, temperature changes in the range of 10-25°C did not affect the removal rates for relatively constant loading rates. This suggests that physical processes were very significant and perhaps controlling in the overall removal processes occurring during the pilot-plant project.

Effluent Polishing

To test effluent polishing characteristics, batch samples of ANFLOW column effluent were conditioned with alum and lime (50 and 60 ppm, respectively) and settled. The resultant supernatant suspended solids values ranged from 10 to 15 ppm. Batch samples of column effluent were also poured downflow through 22 in. of 0.25- to 0.50-mm sand. The suspended solids were reduced from approximately 48 to less than 15 mg/liter by sand filtration.

For on-line tests, a granular media filter was added to the pilot-plant facilities and used to treat a sidestream of the column effluent for 3 weeks. The filter bed was dual media with the following characteristics:

Sand layer - 12 in. deep, 0.45-mm grain

Coal layer - 18 in. deep, 1.00-mm grain

The filter was operated in a downflow mode at a hydraulic loading rate of 3.2 gpm/ft^2. Under the test conditions, the removal of insoluble matter was approximately 70%. The average effluent TSS was 18 ppm, while the average effluent BOD was 33 ppm. Operational difficulties with the small-scale filter system were experienced during these tests. It

ORNL DWG 78-5263

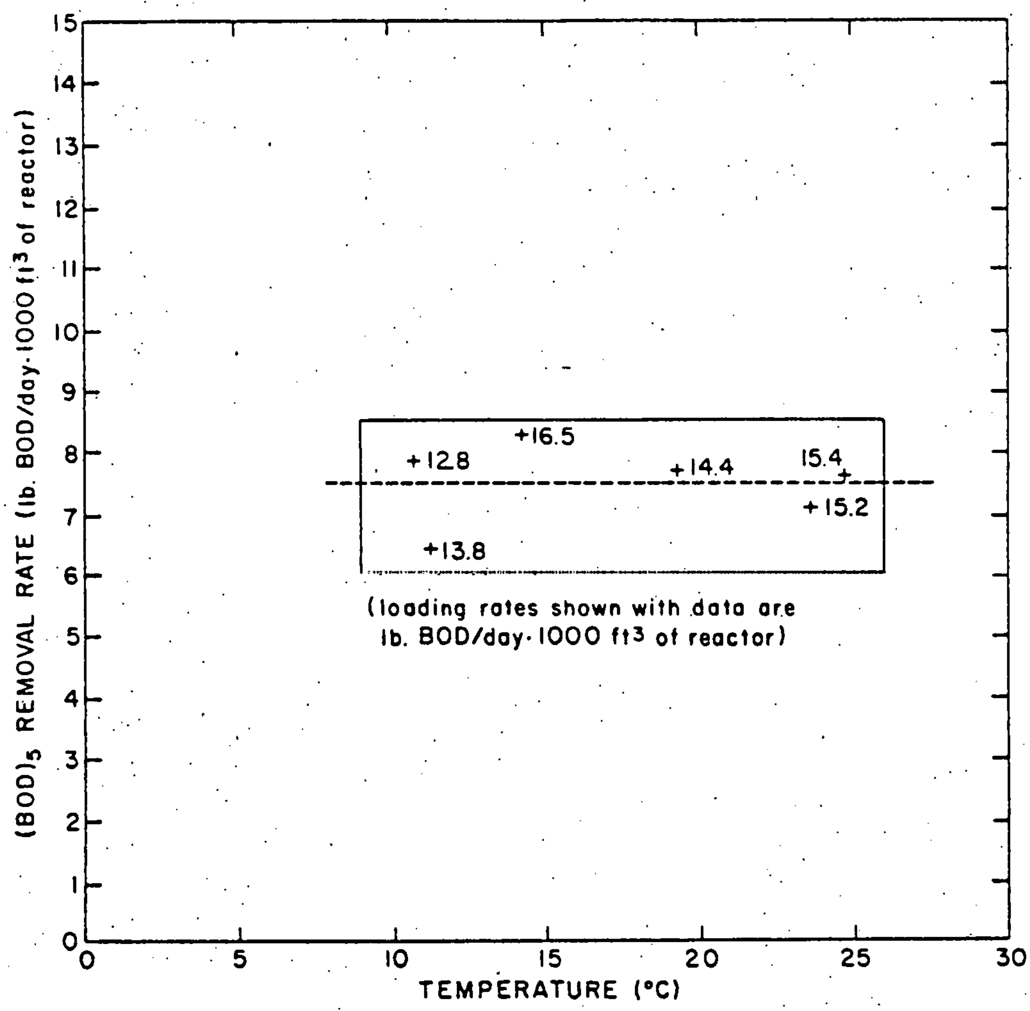

Fig. 12. Effect of temperature on BOD removal rates under constant loading at the ANFLOW pilot plant.

was predicted that better performance would be achieved by optimizing the backwash frequency and by employing chemical conditioning prior to filtration.

Flow Distribution

The hydraulic residence time for wastewater being treated by the ANFLOW column was investigated by residence time distribution (RTD) tests performed at different feed rates. For each test, a dye pulse (19 liters of 10 ppm fluorescein) was introduced into the column through the feed-line standpipe. The column effluent was sampled continuously and combined with a reagent development stream (0.5 M NaOH, 0.005 M EDTA) before being monitored by a fluorometer. The reagent development stream produced a basic pH that enhanced the fluorescence of the dye; the EDTA complexed dissolved-metal ions to prevent precipitation in the flow cell at the basic pH. Results of the RTDs, compared with theoretical plug-flow residence times, are shown in Fig. 13. Two theoretical curves are shown, the first calculated for the actual void volume measured in the packed section of the column and the second calculated for the combined volumes of the packed section and the bottom cone on the column. Since flow was introduced immediately below the packed section (see Fig. 1), it can be assumed that there was little circulation of wastewater in the bottom cone. Therefore, the theoretical curve calculated for the packed section can be used as a model for plug-flow behavior in the column. As seen by the experimental results in Fig. 13, the flow in the ANFLOW column could be approximately described by plug-flow models for feed rates ranging from 1000 to 7000 gpd. No significant channeling problems were indicated for flow in the ANFLOW column.

ORNL DWG 79-903

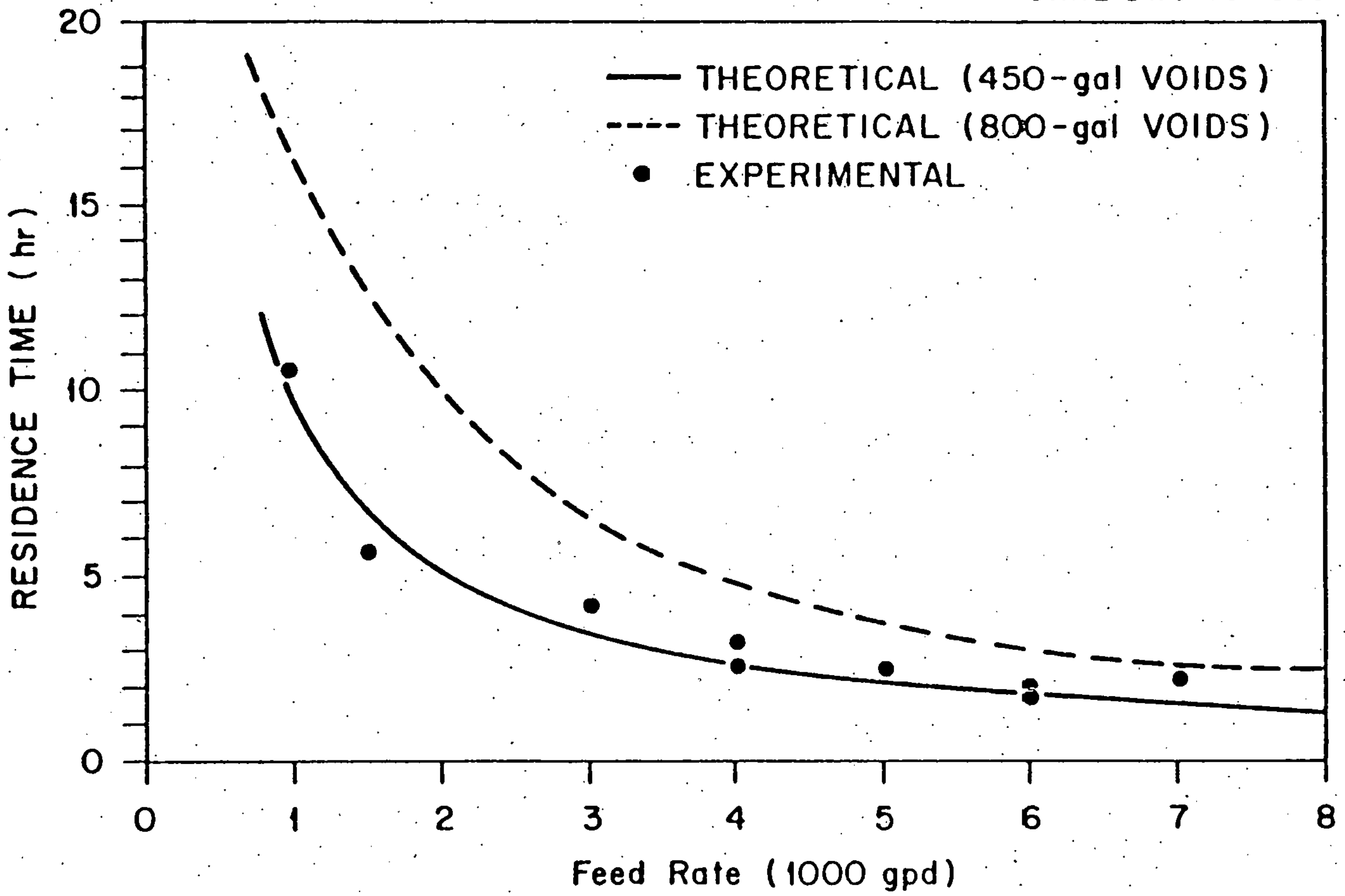

Fig. 13. Hydraulic residence times in ANFLOW bioreactor.

DISMANTLING THE ANFLOW COLUMN

At the conclusion of the pilot-plant operation, the ANFLOW column was drained and the top was opened to allow removal of packing material and accumulated solids. An initial volume increment of 150 gal was collected from the bottom cone; this slurry was 60 vol % solids, produced little odor, and had the qualitative appearance of primary digestor effluent. An additional 650 gal were drained; this mixture was 1.7 wt % solids, and 60% of these solids were volatile. From these measurements it was estimated that 600 gal (or 5000 lb or 80 ft^3) of fixed material (material not removed by draining the column) accumulated in the column during the 2 years of operation. Therefore, approximately 43% of the initial void volume in the packed section remained open to flow after this period.

Of the material remaining as films on the packing surface or in the cores of the packing, approximately 50% was volatile. All film material could be easily removed with a cold-water spray. However, it was obvious that a more open-structured packing material would allow greater efficiency in solids removal during a column draining operation.

The packing was removed from the column in layers starting at the top. There were no radial profiles observed in film thickness at any height above the feed point, and the column did not appear to be plugged at any point. Film thicknesses were observed to be greater in the lower regions of the column where material also accumulated in the cores of the packing material.

CONCEPTUAL DESIGNS FOR TOTAL TREATMENT SYSTEMS

Using pilot-plant data developed by ORNL and their professional experience, AWARE developed engineering conceptual designs for total treatment systems based on the ANFLOW bioreactor. These systems were designed to treat wastewater flow rates of 0.05 and 1.0 mgd while producing an effluent meeting EPA's secondary treatment requirements. Design and operational considerations were developed for both strong and weak wastewaters as defined in Table 1. AWARE summarized these considerations in a report to ORNL (3) and will present them at a later conference (4).

Table 1. Wastewater characteristics

Quality characteristic	Strong wastewater	Weak wastewater
TSS, ppm	350	100
VSS, ppm	275	70
Settleable solids, ppm	20	5
BOD, ppm	300	100
TOC, ppm	300	100
COD, ppm	1,000	250
TKN, ppm	85	20
NH_3-N, ppm	50	12
Temperature (°C),[a]		
Summer	20	20
Winter	15	15

[a]Raw sewage temperature.

The basic design developed by AWARE is shown in Fig. 14. The design includes pretreatment and effluent polishing facilities common to most conventional treatment technologies producing an effluent meeting

ORNL DWG 79-883R

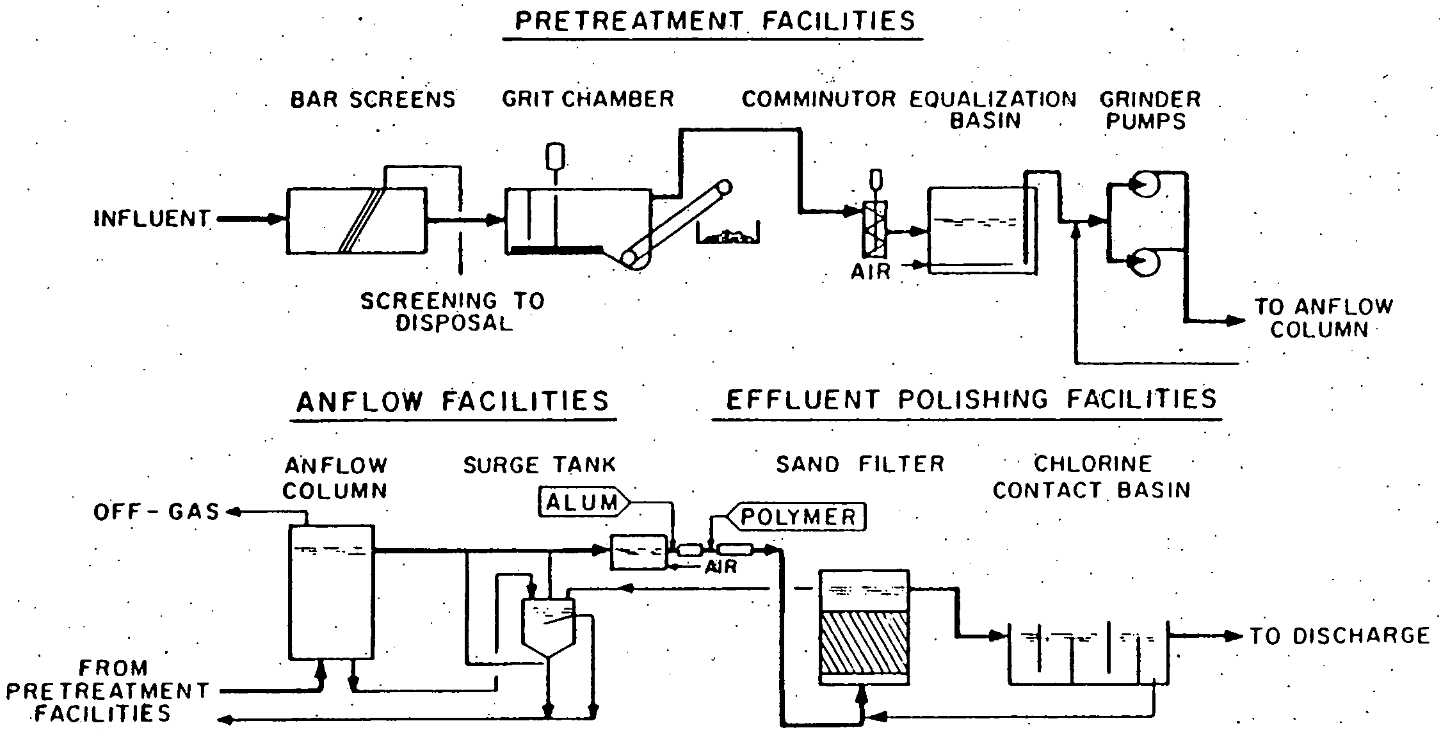

Fig. 14. Process flow diagram for the ANFLOW system.

EPA's secondary treatment requirements. These facilities were designed to complement the wastewater treatment processes occurring in the ANFLOW column. As wastewaters rise continuously through the ANFLOW column, treatment is accomplished by three basic mechanisms: gravitational settling, biophysical filtration, and biological decomposition of carbonaceous wastes. Off-gases produced by the anaerobic processes are expected to be approximately 75% methane, with the remainder being typically a mixture of carbon dioxide and nitrogen. These off-gases are recovered from a vapor disengagement space above the liquid outflow in the ANFLOW column. Sludges produced by the column (slowly or non-degrading solids and excess bacterial populations) are periodically removed by draining the contents of the ANFLOW column into a surge tank. After settling occurs in the surge tank, liquids are recycled through grinder pumps which feed the ANFLOW column. Solids are removed to drying beds or directly to land application, depending on the flow rate of wastewater being treated.

The ANFLOW column was sized using a design HLR of 0.10 gpm/ft^2, which corresponds to a feed rate of 2800 gpd, and a maximum HLR of 0.15 gpm/ft^2, which corresponds to a feed rate of 4200 gpd. AWARE made these decisions using the information contained in Fig. 8. Based on data obtained since AWARE's study, ORNL would propose that a design HLR of 0.25 gpm/ft^2 be used to size ANFLOW columns. The feasibility of this HLR, which corresponds to a feed rate of 7000 gpd, was shown in Fig. 9.

The effluent from the ANFLOW column may be subjected to re-aeration or chemical additions before being filtered. Re-aeration is provided for further reduction in BOD associated with soluble organics, for methane stripping, and for control of the dissolved oxygen content in the final effluent. Chemical addition may be required when weak wastewaters are being treated and final effluents are required to contain less than 15 ppm of either BOD or TSS. Backwash from the sand filter is settled in the surge tank and handled like the drainage from the ANFLOW column.

COMPARATIVE EVALUATIONS OF COSTS AND ENERGY CONSERVATION

To assist in evaluating the technology, AWARE developed comparisons between the wastewater treatment system based on an ANFLOW bioreactor (Fig. 14) and a system based on a version of the activated sludge process (Fig. 15). The designs were developed using their professional experience and their evaluations of the ANFLOW pilot-plant data developed by ORNL. ORNL had previously reported comparisons between an ANFLOW system and another version of the activated sludge process and between an ANFLOW system and the trickling filter process (1,5).

The comparisons developed by AWARE for costs and energy consumption are summarized in Tables 2-5. The comparisons between 1-mgd systems based on ANFLOW with 1-mgd systems based on activated sludge showed that the ANFLOW system used 60% of the energy used by the activated sludge system when weak wastewaters were treated, and 30% of the energy when strong wastewaters were treated. For 0.05-mgd systems, ANFLOW used 55% of the energy used by activated sludge when weak wastewaters were treated, and 47% of the energy when strong wastewaters were treated.

When energy consumption terms necessary for both the ANFLOW and the activated sludge systems (i.e., screening, comminuting, pumping, chlorination) were excluded from these comparative analyses, and only areas of

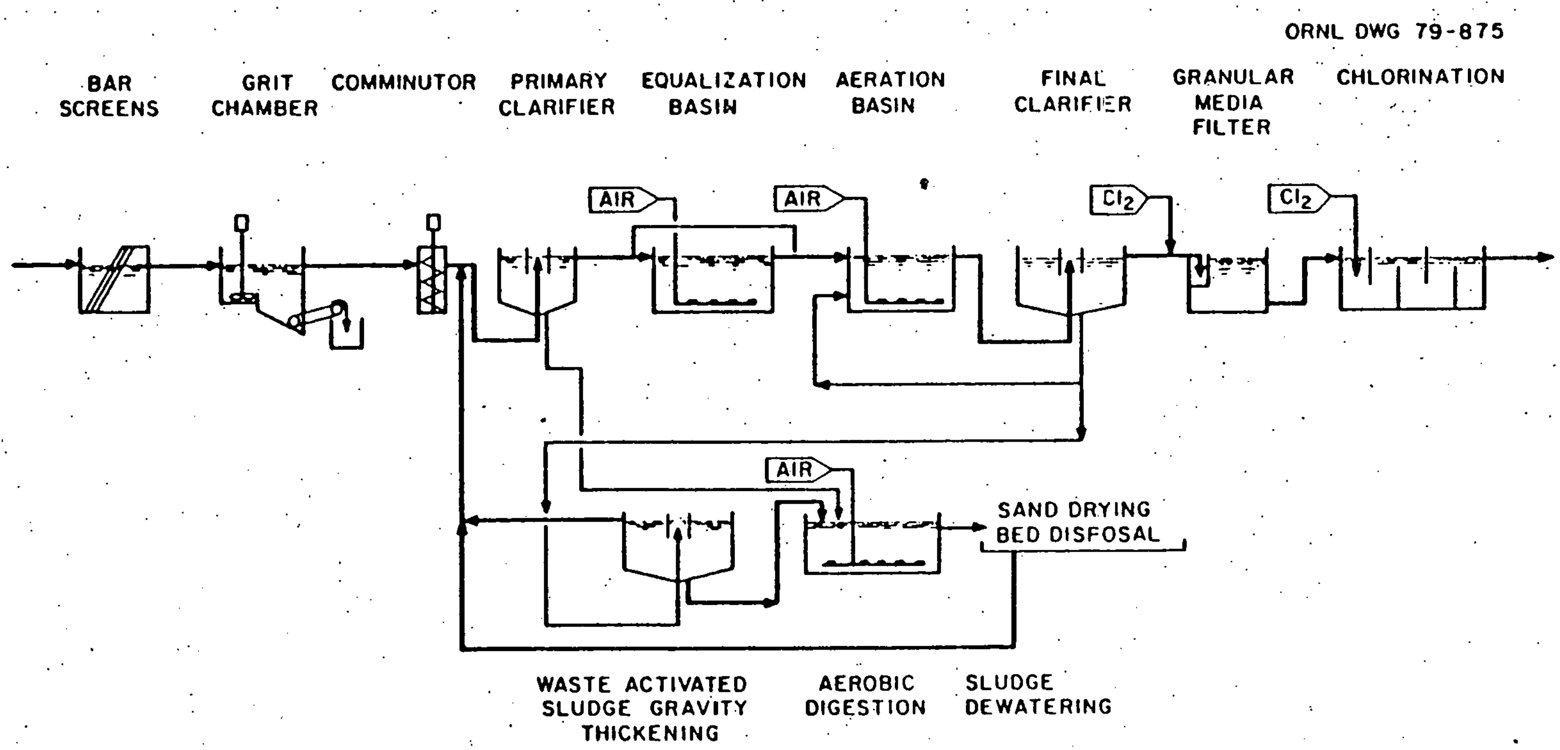

Fig. 15. Process flow diagram for the activated sludge system.

potential energy conservation were considered, the significance of the ANFLOW development was highlighted. For 1-mgd systems, ANFLOW used only 6% of the energy used by activated sludge when weak wastewaters were treated; for strong wastewaters, ANFLOW used only 8% of the energy used by activated sludge. For 0.05-mgd systems, ANFLOW used only 15% of the energy used by activated sludge when weak wastewaters were treated; for strong wastewaters, ANFLOW used only 12% of the energy used by activated sludge. Obviously, the importance of this energy conservation will increase in the future. Notably, approximately 86% of the wastewater treatment facilities projected for operation in this country in 1983 will treat 1.0 mgd or less. In total cost analyses, the ratio of energy costs to capital and operating costs will also obviously increase. It should be particularly noticed from the analyses described above that the energy recovered from methane production (40% conversion efficiency to electricity) in the 1-mgd plant was more than the energy required to operate the plant.

From Table 2 it can be seen that the treatment system based on the ANFLOW bioreactor required a lower capital investment than the activated sludge system for a design flow rate of 0.05 mgd. It can also be noted from Table 3 that approximately 36% of the capital cost of the ANFLOW system was associated with the column and packing material. Since there is no economy of scale associated with the packed column as design flow rates are increased, there will be apparently be a maximum wastewater flow rate which can be economically treated with ANFLOW systems. At a design flow rate of 1 mgd, as seen in Table 4, the capital costs for an ANFLOW system were greater than those for an activated sludge system. However, as seen from Table 5, approximately 60% of ANFLOW capital costs

Table 2.
Comparative capital cost, labor, and power requirements
for a 0.05-mgd treatment system

Unit process	Capital cost ($)				O&M labor requirements (man-hr/yr)				Power requirements (kW)			
	ANFLOW System		Activated Sludge		ANFLOW System		Activated Sludge		ANFLOW System		Activated Sludge	
	Low BOD[a]	High BOD[b]	Low BOD[a]	High BOD[b]	Low BOD[a]	High BOD[b]	Low BOD[a]	High BOD[b]	Low BOD[a]	High BOD[b]	Low BOD[a]	High BOD[b]
Preliminary treatment												
Screening												
Flow measurement	15000	15000	15000	15000	300	300	300	300	1.33	1.22	1.33	1.33
Grit collection												
Comminutor	5000	5000	5000	5000								
Pumping	4000	4000	2500	2500	50	50	25	25	0.95	0.95	0.95	0.95
Equalization	30000	30000	30000	30000	175	175	175	175	0.95	0.95	0.76	0.76
Primary clarification												
Subtotal	54000	54000	52500	52500	525	525	500	500	3.23	3.23	3.04	3.04
Biological treatment												
Packed column	77300	77300			350	450			0.76	0.95		
Re-aeration & surge tanks	15000	15000					200	275				
Aeration & clarification			80000	120000							1.90	3.81
Subtotal	92300	92300	80000	12000	350	450	200	275	0.76	0.95	1.90	3.81
Effluent polishing												
Chlorination	22500	22500	22500	22500	110	110	110	110	0.38	0.38	0.38	0.38
Gradular media filtration	30000	30000	30000		133	133	133		0.76	0.76	0.76	
Subtotal	52500	52500	52500	22500	243	243	243	110	1.14	1.14	1.14	0.38
Sludge handling												
Gravity thickening			17500	17500			90	90			0.38	0.38
Aerobic digestion			20000	40000			10	20			2.85	3.81
Sand drying beds	15000	25000	20000	20000	270	360	495	495				
Subtotal	15000	25000	57500	77500	270	360	595	605	0.0	0.0	3.23	4.19
Total (process costs)	213800	223800	242500	272500	1388	1578	1538	1490	5.13	5.32	9.31	11.42
Other (costs)	106900	111900	121250	136250								
Total (system costs)	320700	335700	363750	408750								

[a]Effluent requirements of 15 μg/liter BOD & TSS
[b]Effluent requirements of 30 μg/liter BOD & TSS

Note: ANFLOW power costs include no energy recovery.
ANFLOW column costs for 3-in. plastic ring.

Table 3.
Comparative capital cost, labor, and power percentages
for a 0.05-mgd treatment system

Unit process	Capital cost (%) ANFLOW System Low BOD	Capital cost (%) ANFLOW System High BOD	Capital cost (%) Activated Sludge Low BOD	Capital cost (%) Activated Sludge High BOD	O&M Labor requirements (%) ANFLOW System Low BOD	O&M Labor requirements (%) ANFLOW System High BOD	O&M Labor requirements (%) Activated Sludge Low BOD	O&M Labor requirements (%) Activated Sludge High BOD	Power requirements (%) ANFLOW System Low BOD	Power requirements (%) ANFLOW System High BOD	Power requirements (%) Activated Sludge Low BOD	Power requirements (%) Activated Sludge High BOD
Preliminary Treatment												
Screening, Flow measurement, Grit collection	7.0	6.7	6.2	5.5	21.6	19.0	19.5	20.1	25.9	25.0	14.3	11.6
Comminutor	2.3	2.2	2.1	1.8								
Pumping	1.9	1.1	1.0	0.9	3.6	3.1	1.6	1.7	18.5	17.8	10.2	8.3
Equalization	14.0	13.4	12.3	11.0	12.6	11.1	11.4	11.8	18.5	17.8	8.2	6.7
Primary clarifier												
Subtotal	25.2	23.4	21.6	19.2	37.8	33.2	32.5	33.6	62.9	60.6	32.7	26.6
Biological treatment												
Packed column	36.3	35.3			25.2	28.6			14.9	17.8		
Re-aeration & surge tank	7.0	6.7										
Aeration & clarification			33.2	44.2			13.0	18.5			20.4	33.4
Subtotal	43.3	42.0	33.2	44.2	25.2	28.6	13.0	18.5	14.9	17.8	20.4	33.4
Effluent polishing												
Chlorination	10.5	10.0	9.3	8.2	7.9	7.0	7.1	7.4	7.4	7.4	4.1	3.3
Granular media filtrations	14.0	13.4	12.3		9.6	8.4	8.6		14.8	14.2	8.2	
Subtotal	24.5	23.4	21.6	8.2	17.5	15.4	15.7	7.4	22.2	21.6	12.3	3.3
Sludge handling												
Gravity thickening			7.2	6.4			5.9	6.0			4.1	3.3
Aerobic digestion			8.2	14.7			0.7	1.3			30.5	33.4
Sand drying beds	7.0	11.2	8.2	7.3	19.5	22.8	32.2	33.2				
Subtotal	7.0	11.2	23.6	28.4	19.5	22.8	38.8	40.5	0.0	0.0	34.6	36.7
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 4.
Comparative capital cost, labor and power requirements
for a 1.0-mgd treatment system

Unit process	Capital cost ($)				O&M Labor requirements (man-hr/yr)				Power requirements (kW)			
	ANFLOW System		Activated Sludge		ANFLOW System		Activated Sludge		ANFLOW System		Activated Sludge	
	Low BOD[a]	High BOD[b]	Low BOD[a]	High BOD[b]	Low BOD[a]	High BOD[b]	Low BOD[a]	High BOD[b]	Low BOD[a]	High BOD[b]	Low BOD[a]	High BOD[b]
Preliminary treatment												
Screening, Flow measurement, Grit collection	55000	55000	55000	55000	1000	1000	1000	1000	2.66	2.66	2.66	2.66
Comminutor	17500	17500	17500	17500								
Pumping	30000	30000	30000	30000	400	400	200	200	19.02	19.02	11.41	11.41
Equalization	95000	95000	95000	95000	700	700	700	700	9.51	9.51	9.51	9.51
Primary clarification			120000	120000			600	600			6.70	6.70
Subtotal	197500	197500	317500	317500	2100	2100	2500	2500	31.19	31.19	30.28	30.28
Biological treatment												
Packed column[c]	841100	951500			1600	2000			1.90	3.80		
Re-aeration & surge tanks	100000	100000										
Aeration & clarification			350000	515000			2000	2750			19.03	57.08
Subtotal	941100	1051500	350000	515000	1600	2000	2000	2750	1.90	3.80	19.03	57.08
Effluent polishing												
Chlorination	75000	75000	75000	75000	310	310	310	310	0.95	0.95	0.95	0.95
Granular media filtrations	200000	200000	200000		1000	1000	1000		5.71	5.71	5.71	
Subtotal	275000	275000	275000	75000	1310	1310	1310	310	6.66	6.66	6.66	0.95
Sludge handling												
Gravity thickening			25000	40000			135	225			0.38	0.38
Aerobic digestion			80000	200000			30	100			11.41	57.07
Sand drying beds	55000	110000	45000	115000	540	1080	675	1080				
Subtotal	55000	110000	150000	355000	540	1080	840	1405	0.0	0.0	11.79	57.45
Total (process costs)	1468600	1634000	1072500	1242500	5550	6490	6650	6965	39.75	41.65	67.76	145.76
Other (costs)	734300	817000	536250	621250								
Total (system costs)	2202900	2451000	1608750	1863750								
Total (energy requirements) with power recovery									0.0	0.0	67.76	145.76

[a]Effluent requirements of 15 μg/liter BOD & TSS.
[b]Effluent requirements of 30 μg/liter BOD & TSS.

Note: [c]ANFLOW column costs for 3- in. plastic rings.

Table 5.
Comparative capital cost, labor, and power percentages for a 1.0-mgd treatment system

Unit process	Capital cost (%)				O&M labor requirements (%)				Power requirements (%)			
	ANFLOW System		Activated Sludge		ANFLOW System		Activated Sludge		ANFLOW System		Activated Sludge	
	Low BOD	High BOD	Low BOD	High BOD	Low BOD	High BOD	Low BOD	High BOD	Low BOD	High BOD	Low BOD	High BOD
Preliminary treatment												
Screening, Flow measurement, Grit collection	3.7	3.4	5.1	4.4	18.0	15.4	15.0	14.4	6.7	6.4	3.9	1.8
Comminutor	1.2	1.1	1.6	1.4								
Pumping	2.0	1.8	0.9	0.8	7.2	6.2	3.0	2.9	47.8	45.7	16.8	7.8
Equalization	6.5	5.8	8.9	7.6	12.6	10.8	10.5	10.0	23.9	22.8	14.0	6.5
Primary clarifier			11.2	9.7			9.0	8.6			9.9	4.6
Subtotal	13.4	12.1	27.7	23.9	37.8	32.4	37.5	35.9	78.4	74.9	44.6	20.7
Biological treatment												
Packed column	57.3	58.3			28.8	30.8			4.8	9.1		
Re-aeration & surge tanks	6.8	6.1										
Aeration & clarification			32.7	41.5			30.1	39.6			28.2	39.2
Subtotal	64.1	64.4	32.7	41.5	28.8	30.8	30.1	39.6	4.8	9.1	28.2	39.2
Effluent polishing												
Chlorination	5.1	4.6	7.0	6.0	5.6	4.8	4.7	4.4	2.4	2.3	1.4	0.7
Granular media filtrations	13.6	12.2	18.6		18.0	15.4	15.0		14.4	13.7	8.4	
Subtotal	18.7	16.8	25.6	6.0	23.6	20.2	19.7	4.4	16.8	16.0	9.8	0.7
Sludge handling												
Gravity thickening			2.3	3.2			2.0	3.2			0.6	0.3
Aerobic digestion			7.5	16.1			0.5	1.4			16.8	39.1
Sand drying beds	3.8	6.7	4.2	9.3	9.8	16.6	10.2	15.5				
Subtotal	3.8	6.7	14.0	28.6	9.8	16.6	12.7	20.1	0.0	0.0	17.4	39.4
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

were associated with the column and packing at this flow rate. Since it is anticipated that continuing development of the process will result in basing future designs on an HLR that is approximately twice the value used in these analyses, the costs of the ANFLOW column and packing could be reduced. Finally, it should be noted that even using the conservative costs given in Table 4, the total annual costs (amortized capital, labor and operating costs) for the ANFLOW system were $297,000 compared to $306,000 for the activated sludge system.

CONCLUSIONS

The development of an energy-conserving wastewater treatment system based on a fixed-film, anaerobic bioreactor has been pursued through 2 years of pilot-plant work by Oak Ridge National Laboratory. As a result, conceptual designs for large-scale treatment systems have been developed and analyzed. These systems meet the EPA's standards for secondary treatment, require significantly less energy to operate than conventional systems, and incorporate in their design the recovery of significant quantities of the methane produced by the anaerobic decomposition of carbonaceous wastes. They have also demonstrated both simplicity and inherent stability in their operation. Projected applications for the treatment of wastewater flow rates as high as 1 mgd encompass approximately 86% of publically owned treatment works in this country. ORNL is presently planning a 50,000-gpd demonstration project to investigate and enhance possibilities for commercialization of this new technology.

ACKNOWLEDGEMENTS

The authors would like to acknowledge H. L. Jennings, T. V. Dinsmore, and R. L. Armstrong of ORNL for their capable operation of the pilot plant during the project and for their assistance in data collection and analysis; J. Robertson of the Oak Ridge East Treatment Plant for his interest, advice, and cooperation on behalf of the city; and S. Shelby, A. Clarke, L. Perry, R. Harris, and Y. Argaman of AWARE for their assistance in evaluating the technology.

REFERENCES

1. R. K. Genung, D. L. Million, C. W. Hancher, and W. W. Pitt, Jr., "Pilot Plant Demonstration of an Anaerobic Fixed-Film Bioreactor for Wastewater Treatment," Biotech. Bioeng. Symp. No. 8 329 (1978).
2. A. L. Compere and W. L. Griffith, "Bioconversion of Wastes to Higher-Valued Organic Chemicals," presented at University of Miami Conference: Energy Conservation - A National Forum, Ft. Lauderdale, Florida, December 1975.
3. G. M. Davis and J. H. Koon, "Evaluation and Engineering Application of the ANFLOW System," contract report prepared by Associated Water and Air Resources Engineers, Inc., Nashville, Tenn. for Oak Ridge National Laboratory, November 1978.
4. G. M. Davis, J. H. Koon, R. K. Genung, and W. W. Pitt, Jr., "Design Studies for Wastewater Treatment Systems Based on Fixed-Film, Anaerobic Bioreactors," to be presented at the Energy Optimization of Water and Wastewater Management for Municipal and Industrial Applications Conference, December 1979, sponsored by the Urban Waste and Municipal Systems Branch, Department of Energy. Proceedings to be published.
5. W. L. Griffith, Economics of the ANFLOW Process for Municipal Sewage Treatment, "ORNL/TM-6574 (March 1979).

LIST OF FIGURES