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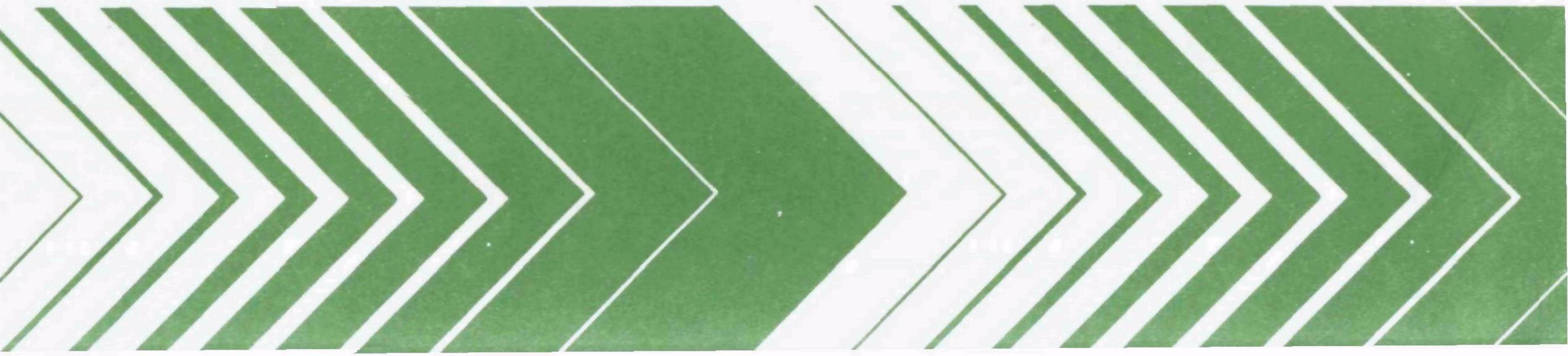
Expanded Bed Biological Treatment



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EXPANDED BED BIOLOGICAL TREATMENT

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of our environment and the interplay between its components require a concentrated and integrated attack on the pollution problem.

Research and development is the necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This report describes the results of a pilot-scale evaluation of a novel secondary wastewater treatment process, Expanded Bed Biological Treatment. The process is designed to achieve rapid removal of organic pollutants from settled wastewater by contacting it with high concentrations of microorganisms in a three phase (wastewater, oxygen gas, inert media) fluidized bed reactor.

Francis T. Mayo
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ABSTRACT

A three-year pilot-scale research investigation at the EPA Lebanon Pilot Plant was conducted to evaluate the feasibility of a unique biological secondary treatment process, designated the Expanded Bed Biological Treatment Process (EBBT).

The EBBT process is a three-phase (oxygen/wastewater/sand media) fluidized bed contacting system in which settled wastewater is passed upwards through a series of two to eight columnar reactors partially filled with fine sand particles. The velocity of the wastewater flow is sufficient to keep the sand particles in suspension. The result is a fluidized bed of sand which provides a large surface area upon which bacteria can grow. These bacteria remove contaminants from the wastewater as it passes by. An aerobic environment is provided by cocurrently feeding high-purity oxygen gas into the base of each reactor or preferably by diffusing it into the wastewater before it enters each reactor.

The pilot-scale system was operated at flows ranging from 7.6 to 30.2 ℓ/min (3 to 8 gpm) and reactor rise rates of 163 to 816 ℓ/min/m^2 (4 to 20 gpm/ft^2). System empty bed hydraulic retention times ranged from 15 minutes to 52 minutes in the testing.

The EBBT process achieved an average TCOD removal efficiency of 75 percent and an effluent TCOD of 48.8 mg/ℓ (13 mg/ℓ/$TBOD_5$) at an empty bed retention time of 44 minutes and a TCOD volumetric organic loading rate of 6.4 kg/m^3/day (400 lb/1000 ft^3/day). Secondary effluent guideline quality effluent was achieved at empty bed retention times as short as 25 minutes.

The EBBT unit operated at mixed liquor volatile suspended solids concentrations in the range of 14,000 to 16,000 mg/ℓ. Individual reactor concentrations ranged as high as 30,000 mg/ℓ. The highly concentrated biomass contributed to the rapid reaction rates experienced.

Net waste solids production for the process ranged from 0.26 to 0.57 kg VSS/kg TCOD removed. The solids retention time ranged from 8.7 days to 5.2 days, respectively. The waste solids production values are in a range comparable to that reported for many suspended growth oxygen activated sludge systems.

The ability to maintain stable fluidized bed conditions was found to be a critical operational factor. The degree of system instability was a function of the amount of sand support media lost to the process effluent daily and transported between reactors in the system. Daily loss rates in excess of 1.0

percent of the total system wet sand weight were found to cause severe plugging of the process lines, excess washout of bacterial mass, and poor treatment performance. The principal causes of sand bed instability were found to be: 1) transport of sand media through the system by attachment to rising undissolved oxygen bubbles in the fluidized beds; and 2) over-expansion of the fluidized bed as a consequence of excess biological growths on the sand particles which acted to reduce the effective particle density over a period of process operation.

Physical and monitoring limitations of the pilot-plant system itself resulted in frequent operational difficulties and periods of low process performance. Problems encountered included clogging of process lines, structural failure of system reactors under conditions of excess pressure, and low oxygen gas utilization efficiency (measured at only 38 percent). The low strength of the City of Lebanon wastewater often limited the ability of the process to achieve higher calculated organic removal efficiencies.

The fluidized bed treatment concept employed in EBBT is believed to have substantial potential for application in the wastewater treatment field. The ultimate utility of the process, however, will depend upon the development and demonstration of: an effective means of controlling the amount of biological growth per media particle; a means of dissolving high quantities of oxygen gas external to the reactor to avoid three-phase conditions; and a system for achieving oxygen utilization efficiencies in excess of 90 percent.

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ACKNOWLEDGEMENT

The authors wish to thank the operating staff of the Lebanon Pilot Plant for their determination, patience, and contribution in the conduct of this work. Particular recognition belongs to Richard Spellmire, Selden Heath, Jerry Burden, Albert Oberschlake, and James Bond.

SECTION 1

INTRODUCTION

In April 1970, a research investigation was initiated at the Environmental Protection Agency's Lebanon Pilot Plant in Lebanon, Ohio, to evaluate the feasibility of a unique secondary biological treatment concept. The wastewater treatment concept which evolved from these investigations is the Expanded Bed Biological Treatment System (EBBT).

EBBT is a three-phase (oxygen-wastewater-sand) fluidized bed contacting system. Wastewater is passed upwards through a series of columnar reactors partially filled with fine sand particles. The velocity of wastewater flow is sufficient to keep the sand grains in suspension. The result is an expanded (or fluidized) bed of sand which provides a large surface area upon which bacteria can grow. These bacteria remove contaminants from the wastewater as it passes by. An aerobic environment is provided by cocurrently feeding high-purity oxygen gas into the base of each reactor or by diffusing it into the wastewater before it enters each reactor.

The EBBT system is capable of removing a greater amount of contaminant per unit volume of reactor than currently available suspended growth air or high-purity oxygen biological treatment processes. This is possible because of the significantly increased effective treatment surface area and the higher concentrations of active organisms which are possible in the system.

This report outlines the background of the EBBT concept and summarizes the results of the pilot scale investigations at the Lebanon Pilot Plant.

SECTION 2

CONCLUSIONS

The EBBT system tested at the EPA Lebanon Pilot Plant represents a potentially valuable secondary wastewater treatment process. The system was capable of producing an effluent wastewater meeting proposed secondary effluent quality guidelines at an empty bed retention time (based on Q) as short as 25 minutes. At an empty bed retention time of 44 minutes the system achieved an average TCOD removal efficiency of 75 percent, while producing an effluent TCOD of 48.8 mg/l (13 mg/l $TBOD_5$). This was at a TCOD volumetric organic loading rate of 6.4 kg/m^3/day (400 lb/1000 ft^3/day).

The EBBT unit was capable of operating at mixed liquor volatile suspended solids concentrations in the range of 14,000 to 16,000 mg/l. Individual reactor concentrations ranged as high as 30,000 mg/l. The highly concentrated biomass contributed to the rapid reaction rates experienced.

Net waste solids production for the process ranged from 0.26 to 0.57 kg VSS/kg TCOD removed. The solids retention time ranged from 8.7 days to 5.2 days respectively. The waste solids production values are in a range comparable to that reported for many suspended growth oxygen activated sludge systems.

The ability to maintain stable fluidized bed conditions was found to be a critical operational factor. The degree of system instability was a function of the amount of sand support media lost to the process effluent daily and transported between reactors in the system. Loss rates in excess of 1.0 percent of the total system wet sand weight were found to cause severe plugging of the process lines,excess washout of bacterial mass, and poor treatment performance. The principal causes of sand bed instability were found to be: 1) transport of sand media through the system by attachment to rising undissolved oxygen bubbles in the fluidized beds; and 2) over-expansion of the fluidized bed as a consequence of excess biological growths on the sand particles which acted to reduce the effective particle density over a period of process operation. The ultimate utility of the fluidized bed treatment concept (EBBT) will depend upon the development of an effective means of positively controlling biological growth per media particle and dissolving sufficient oxygen gas external to the fluidized reactor to avoid three-phase conditions.

Oxygen utilization efficiency was measured for one of the fifteen experimental runs. It was found to be only 38 percent, compared to the often greater than 90 percent efficiencies reported for commercially marketed high purity oxygen activated sludge processes. The principal causes of low efficiency were an unoptimized diffuser design and the inability to recycle system off-gases from the pilot plant unit.

The calculation of treatment performance efficiency was often limited by the low strength wastewater at Lebanon, Ohio.

SECTION 3

RECOMMENDATIONS

The pilot scale experiments at the Lebanon Pilot Plant accomplished their objective as a first examination of the feasibility of a fluidized bed biological contacting concept. However, many additional technical considerations require examination and resolution before the process can be moved from development to demonstration. These include:

(1) Additional experimental testing on a reasonable strength wastewater to establish the process relationship between SRT and treatment performance, determine optimal particle biomass, refine yield coefficients, and quantify the impact of temperature and diurnal flow variation upon performance.

(2) Examination of advanced techniques for dissolution of oxygen into the wastewater prior to entering the reactor environment.

(3) Testing of alternative methods of separating excess biological growth from the suspension media for positive control of SRT and percent expansion of the fluidized bed.

(4) Various alternates for final effluent solids separation should be evaluated. The nature of the suspended solids effluent from the final reactor stage in the experimental EBBT system at Lebanon suggests that the requirements may be considerably different from conventional or oxygen activated sludge plants. One alternate would be to design a clarification stage for the top of the final reactor stage. The moderate effluent suspended solids concentration leaving the final reactor stage in the EBBT system (30 mg/l to 50 mg/l) suggests the possibility of direct dual media filtration of reactor effluent as a possibility to be examined.

(5) Any future experimental pilot plants should have at most two stages which are at least 60 cm in diameter to reduce difficulties in pilot operation. The test system should avoid introducing gaseous oxygen into the sand/wastewater environment in the fluidized reactor. A method for positive control of excess biological solids is essential. Provision of a capacity for off-gas recycle to the influent should be considered. The unit should provide for a flow capacity consistent with an operating rise rate of 8 to 20 gpm/ft^2.

SECTION 4

BACKGROUND

The use of attached biological slimes in wastewater treatment is widely reported. Packed beds of various types have been employed for decades, ranging from traditional trickling filter applications to Emscher filters(1), contact aerators, forced aerated trickling filters(2), and the more recent commercially marketed plastic media units. Of special note is a 1935 patent issued to C. C. Hayes (3) which proposed an aerated upflow packed bed system which was designed for both carbonaceous removal and nitrification. Recently, columnar systems for denitrification of nitrified effluents have been demonstrated (4, 5, 6, 7).

The use of a fluidized bed process for biological treatment of secondary wastewater effluent has been reported(8). The process consists of the cocurrent flow of air and wastewater upward through a bed of fluidized sand media. Physical-chemical adsorption of soluble and colloidal material from the dilute final effluent onto the sand particles creates high substrate concentrations at the particle surfaces. This permits the development of biological surface slimes which have been reported to effect 70 to 90 percent removal of the organics in the final effluent. The process is designated the Pulsed Absorption Bed Process (PAB) because of the periodic or pulsed motion created in the fluidized bed as the air bubbles rise through the media.

The addition of coal particles in conventional activated sludge aeration basins has been reported to increase system efficiency by a mechanism similar to that employed in the PAB process(9). The suspended coal particles concentrate nutrients and organic pollutants from the mixed liquor while providing surface area for microbial growth in the "enriched" microenvironment adjacent to the particle.

Several reports have appeared describing an increase in the capacity of activated carbon systems which was attributed to biological growth on the coal particles. Hopkins, et al, reported the development of bacterial slimes on activated carbon particles in expanded bed contactors(10). Some biological removal of organics was accomplished, but the absolute amount was not estimated.

In 1969, the addition of pure oxygen to carbon adsorption columns at the EPA Blue Plains Pilot Plant and at the EPA Pomona Pilot Plant was initiated to examine the potential for nitrification in the column environment resulting from attached biological growths. Moderate nitrification was reported at Blue Plains where lime-clarified secondary effluent was studied (11). Packed beds receiving secondary effluent at Pomona were capable of oxidizing 3 to 4 mg/1 of ammonia to nitrate (4).

The use of pure oxygen in waste treatment is, of course, not a new concept. The potential benefits of using oxygen gas in activated sludge treatment were first recognized by Pirnie (12) when he proposed the so-called "bio-precipitation" process over 20 years ago. Biological success with the process was later achieved at bench scale by Okun (13) and finally at pilot scale by Budd and Lambeth (14). In the past, low oxygen utilization efficiencies for the process precluded its full-scale application. Since 1968, however, the development of "UNOX" process by Union Carbide Corporation (15), the "SIMPLOX" process by Cosmodyne Corporation (16), and the AIRCO pipeline reactor, oxygen activated sludge treatment has progressed rapidly from the drawing board to a full-scale marketed process. The UNOX system, as an example, has been reported capable of attaining BOD_5 and suspended solids removals of 90 percent at a retention time of 1.4 hours (based on Q) while achieving up to 90 percent oxygen utilization efficiency (15).

Since the completion of this investigation, the results of other studies of the treatment of wastewater in fluidized beds have been reported. Jeris, et al., reported the results of testing on municipal wastewater at Nassau County, New York (17). Separate pilot studies at flows ranging from 150,000 to 300,000 1/day (40,000 gpd to 80,000 gpd) were conducted for carbonaceous BOD removal, nitrification and denitrification. BOD removals of 90 percent were reported. Studies have also been reported by Scott and Hancher at the Oak Ridge National Laboratory, using a tapered fluidized bed reactor for biological denitrificaton (18).

The Expanded Bed Biological Treatment concept (EBBT) was designed to combine the acknowledged benefits of oxygen aeration technology and attached growth biological systems into one process. As it was initially conceived, EBBT was intended to be a high-purity oxygen, fixed-film nitrification system. It was hoped that such a system would improve upon the variable nitrification performance of single sludge systems, while overcoming the greater expense of the more reliable two sludge system for nitrification. The intimate contact with surface-bound slimes, greater cell residence times, and use of pure oxygen in EBBT were viewed as key factors to improved performance.

When the expanded bed pilot test program was initiated at the Lebanon Pilot Plant in September 1970, the project scope was expanded to also consider treatment of primary effluent in a staged columnar system designed to achieve both organic removal and nitrification. The research was conducted over a three-year period ending in September 1973.

SECTION 5

PILOT SCALE STUDIES

OBJECTIVES AND PROJECT ORGANIZATION

The primary objective of the research program at Lebanon was to determine the feasibility of pure oxygen biological oxidation of organic wastes with subsequent nitrification of ammonia in a three-phase fluidized bed system. The results were to be used to evaluate process performance in comparison with the best state-of-the-art suspended growth reactor. Increased efficiency over conventional treatment schemes was anticipated due to: 1) high effective mixed liquor biological solids concentrations possible through attached films; 2) the use of high-purity oxygen; 3) shorter required contact times; 4) benefit gained by having to gravity-separate only waste solids from the system; 5) elimination of sludge recycle; and, 6) resistance to shock loads.

The study was divided into four distinct phases. Phase I included a literature review and desk top design of the experimental system. Phase II provided for final design and construction of a 37.8 liter per minute (10 gpm) pilot scale test facility. Phase III consisted of preliminary studies to determine best fluidization conditions, fluidization media, and process flow rates. Phase IV, with which the bulk of this report is concerned, consisted of the actual biological testing. The object in this phase was to determine process kinetics, maximum organic removal efficiency, minimum contact time, oxygen utilization efficiency, and sludge production rates.

PRELIMINARY STUDIES - MEDIA EVALUATION

The first step in the EBBT evaluation involved the selection of a fluidization media suited for use in the reactors. The objective was to provide a particle small enough to maximize the available surface area for bacterial attachment, but with a specific gravity conducive to bed control under fluidized conditions.

The physical test system used in the initial studies was a modification of a pilot-scale system used previously for columnar packed-bed denitrification research (7). The primary concern was ease of media evaluation and not treatment optimization. The unit consisted of five 10.2 cm (4-inch) I.D. columns connected in series. Each column was 3.66 meters (12 feet) high with 27.9 cm (11 inches) of gravel support media in the base. Primary effluent from the city of Lebanon, Ohio Sewage Treatment Plant was pumped into the base of the first column with a variable-speed, positive-displacement pump. Oxygen gas was fed into each column base through 7.6 cm (3-inch) diameter stainless steel diffusers at rates ranging from 100 to 200 cc/min. The system influent and effluent were routinely analyzed for TCOD, SCOD, TOC, SOC, pH, TSS, VSS, temperature, NH_3-N, and NO_3.

The first media examined was No. 1 anthracite coal. A sieve analysis revealed that this coal possessed an effective size of 0.62 mm (mean size 1.0 mm) with a 1.77 coefficient of uniformity. This media is typical of that used in many dual-media filter applications.

Each column was filled with 1.83 meters (6 feet) of coal. The system was then operated for 30 days at a feed rate of 11.6 liters/min (1.75 gpm), which corresponded to a column rise rate of 816 $l/min/m^2$ (20 gpm/ft^2), a rate often employed in filter backwashing. Results were encouraging, as moderate organic removals were obtained during this period (52 percent removal of SCOD, and 32 percent of TOC). However, the coal media proved inadequate as a fluidization media. Bed separation and system plugging were frequent, and a considerable amount of the media washed into the effluent daily. Reduction of column flow rates reduced media loss somehwat, but only at the expense of an increased frequency of column plugging which resulted from incomplete fluidization.

Other media were tested in a similar fashion, some in the 10.2 cm (4-inch) I.D. column system, and others in a larger system (25.4 cm (10-inch) I.D. column, which is described later. These media included:

Medium cinders - sp. gravity 1.1, mean particle diameter 2.0 mm, size distribution 0.21 mm - 26.67 mm

Crushed cinders - mean particle diameter 1.2 mm, size distribution 0.21 mm - 0.373 mm

Hydraulically classified cinders - mean particle diameter 0.5 mm, size distribution 0.420 mm - 1.41 mm

Filter sand - sp. gravity 2.65, mean particle diameter 0.5 mm, size distribution 0.25 mm - 0.85 mm

The hope in employing the cinder material was that the numerous cavities in each particle due to its porous nature would provide a greater surface area for slime growth than the coal. The use of this material, however, was found undesirable for several reasons: 1) the particle size distribution was too extreme; 2) the specific gravity ranged too wide (0.4 to 1.1 g/cc); and, 3) the particles broke down from abrasive contact in the system. This resulted in high rates of media washout and frequency of plugging of the lines connecting the columns.

The fine filter sand proved to be the most satisfactory of those media tested. The physical properties of this sand included an effective size of 0.37 mm (mean particle diameter 0.5 mm) and a coefficient of uniformity of 0.36. The sand's high uniformity and greater density (sp. gravity 2.65 g/cc) produced much more stable fluidized bed conditions. The greater upflow velocity required to suspend the particles not only provided better fluid mixing in the column, but also appeared to reduce the frequency of plugging inside the column.

All tests employing filter sand as bed media were conducted in the larger, 25.4 cm (10-inch) I.D. column system. Once the fluidization requirements and the hydraulic acceptability of the sand were determined, treatment performance testing was initiated. A description of this system and the results obtained are described below.

EXPERIMENTAL RESULTS - TWO-COLUMN SYSTEM

System Description

In November 1970, construction of a larger scale EBBT pilot system was initiated. This system was designed to provide liquid retention times similar to those experienced in the preliminary system, while avoiding some of the hydraulic and mechanical problems experienced with the smaller unit.

The 25.4 cm (10-inch) diameter columnar·unit was completed in late February 1971, and testing with cinder media of various types, as described above was started in April. The media evaluation trials were completed in September 1971, with the selection of the 0.5 mm filter sand as the most promising media.

Figure 1 is a schematic drawing of the two-column system, prior to the initiation of biolgoical studies in September 1971. The unit consisted of two 3.66 m (12-foot) high, 25.4 cm (10-inch) I.D. clear acrylic columns, connected in series. An 8.9 cm (3-1/2 inch) diameter stainless steel diffuser was installed in the base of each column to permit addition of oxygen gas.

The diffusers were mounted below a 1.9 cm (3/4-inch) thick circular PVC flow distribution plate. Approximately 27.9 cm (11 inches) of support gravel was placed above the plate, followed by 1.83 m (6 feet) of the sand media. To limit media washout, a 45.7 cm (18-inch) diameter expanded section was later added to the top of the second stage. It was anticipated that the resulting drop in upflow velocity in the expanded section would prevent suspended sand particles from being carried into the effluent.

Primary effluent from the Lebanon Sewage Treatment Plant was fed into the bottom of the first stage through a variable-speed positive-displacement pump. The effluent from the top of the first stage was then carried under pressure to the base of the second stage through a 3.8 cm (1-1/2 inch) PVC pipe. Stage No. 2 effluent continued to a 661.5 l (175-gallon), 0.71 m^2

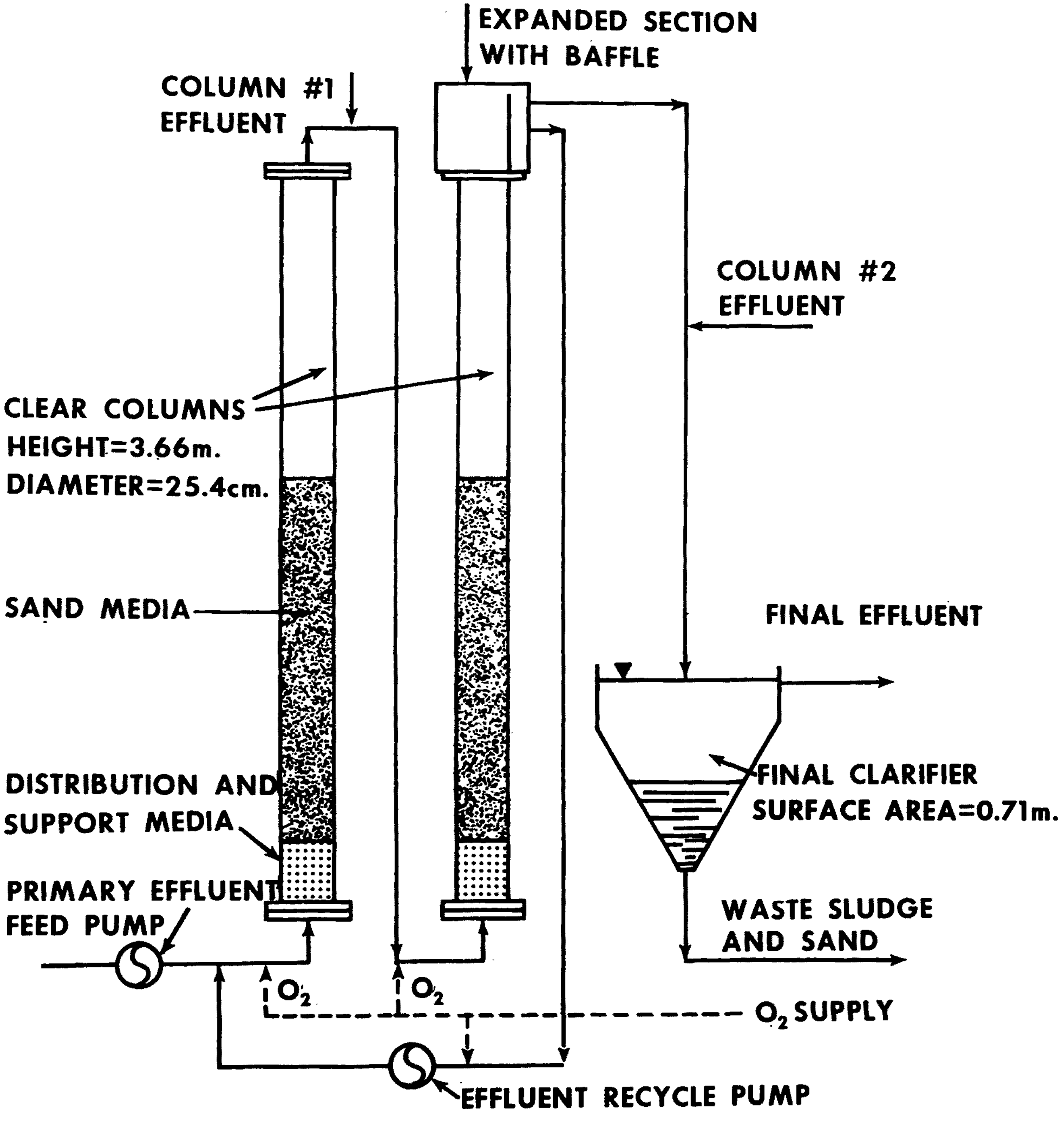

FIGURE 1. EBBT TWO-COLUMN SYSTEM

($7.67\ ft^2$) final clarifier. A portion of the stafe No. 2 effluent could also be recycled by a second variable-speed positive-displacement pump back to the incluent stream. The purpose of this was to add rise-rate control flexibility and limit depletion of the sand beds by recycling a portion of the sand media being lost to the effluent.

Pure oxygen could be supplied to all application points in the system by a bank of three (84.9 m^3) liquid oxygen cylinders. The gas feed pressure was maintained at $28.1 \times 10^3\ kg/m^2$ (40 psig) and the gas was metered to the system through a panel of rotameters. Provision was also made for adding oxygen gas to the suction side of recycle pump. Preliminary testing indicated that up to 20 mg/l dissolved oxygen could be added to the recycle stream in this manner.

Composite samplers were located on the influent and effluent streams of the system. Grab samples could also be obtained from 2.54 cm (1-inch) sample taps located at the base of each column and in the free board space at the top of each column. Provision was not made on the initial unit for measuring system off-gas volume or quality.

Results

A total of six experimental runs were conducted with the two-column system. Runs 1 and 2 were devoted entirely to optimizing system hydraulics and determining the effect of a series of modifications to the expanded section on the second stage. Both runs were of short duration. Significant biological activity was not observed until the end of Run 2.

Run 2 also provided an indication of the hydraulic performance of the sand beds under varying column rise rates. In Figure 2, percent bed expansion as a function of column rise rate is shown for clean sand (minimal attached slimes) under conditions of a 200 cc/minute oxygen feed rate and an initial unexpanded bed height of 190.4 cm (75 inches).

Treatment performance testing began with the initiation of Run 3 on September 30, 1971. The purpose of this and subsequent runs was to first establish a viable microflora on the sand media, and then vary basic operational parameters in a predetermined manner to evaluate: 1) substrate removal efficiency as a function of system empty bed contact time; 2) optimum column rise rate for maximum internal mixing with minimum media washout; 3) the effect of temperature upon performance; 4) maximum effective mixed liquor solids concentration; and, 5) required oxygen rates.

Table 1 summarizes average operating conditions and system performance for Run 3 through Run 6, covering a period from September 30, 1971 through April 7, 1972. Throughout this period the system was monitored 24 hours per day, seven days per week.

From Table 1 it can be seen that the system was operated with empty-bed contact times ranging from 15.5 minutes to 46.6 minutes (based on Q). The column rise rate was varied between $163.2\ l/min/m^2$ ($4\ gpm/ft^2$) and $816\ l/min/m^2$ ($20\ gpm/ft^2$) by adjusting the effluent recycle rate. The

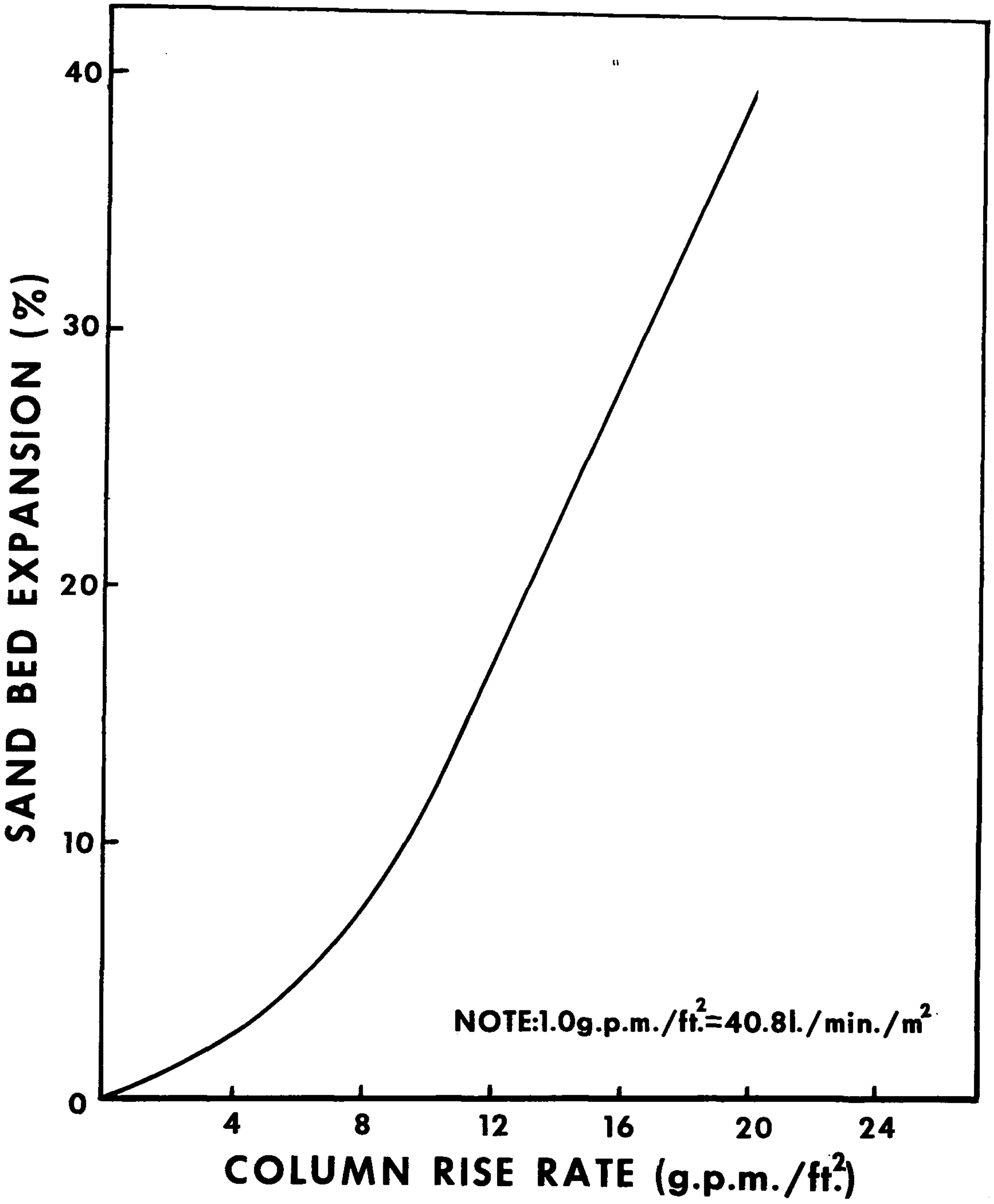

FIGURE 2. BED EXPANSION (CLEAN SAND)
AS A FUNCTION OF RISE RATE

TABLE 1 OPERATIONAL SUMMARY TWO-COLUMN SYSTEM

Parameter	Unit	Run 3	Run 4	Run 5	Run 6
Waste treated		Primary Effluent	Primary Effluent	Primary Effluent	Primary Effluent
Influent temperature	^oC	19.6	18.5	12.8	12.2
Influent flow rate (Q)	l/min	30.2	15.1	7.6	15.1
Recirculation flow rate (R)	l/min	7.6	15.1	0	0
System empty bed contact time (based on Q)	min	15.5	23.3	46.6	23.3
Column rise rate (Q+R)/A	$l/min/m^2$	816	652.8	163.2	326.4
Clarifier overflow rate	$l/min/m^2$	42.6	21.3	10.6	21.3
Oxygen addition rate (at S.T.P.)	cc/min	1233	750	826	1030
(system average)	gms/m^3	46.4	56.5	124.3	77.5
Dissolved oxygen concentration					
influent	mg/l	1.1	1.3	3.3	4.9
stage No. 2 effluent	mg/l	4.0	3.5		7.3
- clarifier effluent	mg/l	2.2	1.5	4.59	8.3
recirculation stream	mg/l	19.6	16.1	18.3	
Performance Summary					
Influent TCOD	mg/l	233.2	230.0	288.8	179.6
SCOD	mg/l	93.3	115.0	78.3	69.9
TOC	mg/l	57.0	71.0	71.3	70.7
SOC	mg/l	29.0	37.0	35.8	28.7
TSS	mg/l	82.0		111.0	84.2
Effluent TCOD	mg/l	171	179	100.0	86.2
SCOD	mg/l	68.2	63.0	36.5	35.7
TOC	mg/l	51.0	52.0	26.1	33.5
SOC	mg/l	21.0	19.0	14.0	15.6
TSS	mg/l	61.0		28.4	32.7
TCOD removal $(\frac{TCODin-TCODout}{TCODin} x100)$	%	26.6	22.2	65.3	52.0
SCOD removal $(\frac{SCODin-SCODout}{SCODin} x100)$	%	26.9	45.2	53.3	48.9
Overall COD removal $(\frac{TCODin-SCODout}{TCODin} x100)$	%	70.7	72.6	87.5	80.1
TOC removal $(\frac{TOCin-TOCout}{TOC\ in} x100)$	%	10.6	26.8	61.8	52.6
TSS removal $(\frac{TSS\,in-TSS\,out}{TSS\,in} x100)$	%	25.6		74.4	61.1

*l/min x 0.265 = gpm 0.0245$_2$
**$l/min/m^2$ x 0.0245 gpm/ft^2
***gms/m^3 x 0.00835 - lbs/1000 gal.

surface overflow rate on the final clarifier ranged from a low of 1.53 x 10^4 l/min/m^2 (375.5 gpm/ft^2) in Run 5 to a high of 6.13 x 10^4 l/min/m^2 (1502 gpm/ft^2) in Run 3, and produced total system suspended solids removal of 74.4 percent and 25.6 percent, respectively.

The oxygen addition rates and dissolved oxygen concentrations for various system locations represent average conditions. Daily and hourly conditions varied somewhat from these values. Average clarifier effluent dissolved oxygen concentrations did not fall below 1.5 mg/l. The dissolved oxygen concentrations in the effluent of stage 2 averaged between 3.5 mg/l (Run 4) and 7.4 mg/l (Run 5) while daily values never fell below 0.8 mg/l in any of the runs.

Table 1 also shows the average wastewater characteristics of the influent and effluent streams. The COD data reveals the relatively low strength of the Lebanon wastewater. Removal efficiencies for both total and soluble COD (TODC and SCOD), organic carbon (TOC and SOC), and total suspended solids (TSS) are given. In terms of monitoring system performance for control purposes, greater significance was attached initially to the removal of soluble waste components, the purpose being to eliminate the effect of any variation in solids settling efficiency in the final clarifier. Soluble COD removal ranged from a high of 55 percent in Run 6 to a low of 26.9 percent in Run 3, representing absolute effluent SCOD values of 35.7 mg/l and 68.2 mg/l, respectively. In most instances higher percent removal values were believed to be limited by the low influent waste strength. The effluent quality during Run 5 and Run 6, for instance, was considered good (36.5 mg/l and 35.7 SCOD, respectively), but on a percent removed basis, performance appeared poor.

Influent and effluent samples were analyzed for five-day biochemical oxygen demand (BOD_5) only periodically to determine the average relationship between BOD_5 and the other performance parameters. The following relationships remained relatively constant throughout the research:

Ratio	EBBT Influent	EBBT Influent
$TCOD/BOD_5$	2.1	3.47
TOC/BOD_5	1.0	0.62

The calculated effluent BOD_5 using these ratios ranged from approximately 32 mg/l in Runs 3 and 4 to 16 mg/l in Run 5 and 21 mg/l in Run 6. BOD_5 removal efficiency ranged from a low of 44 percent in Run 3 to a high of 77 percent in Run 5. Treatment efficiency was directly proportional to the empty bed contact time employed (based on Q and the total empty column volume). Best removals were obtained at the empty bed contact time of 46.6 minutes while reduced treatment efficiency was experienced at the shortest contact time (15.5 minutes).

Process performance can be described in terms of a parameter defined as overall COD removal:

$$\% = \frac{\text{TCODin} - \text{SCODout}}{\text{TCODin}} \times 100$$

A number of studies have suggested that effluent SCOD is a better indicator of the quantity of residual organic matter in biological treatment process effluents than is BOD_5 (18)(19). The measurement of COD is recommended in lieu of BOD_5 because of the recognized time and reproducibility limitations of the standard BOD_5 test. The calculation of overall COD removal acknowledges that suspended material present in the system influent wastewater can be regarded as potential substrate for the microorganisms and not as cells. The use of effluent soluble COD is designed to exclude sludge cells from effluent residual organics and to divorce process biological (kinetic) performance from final clarifier efficiency.

One drawback to the use of overall COD removal as an indicator of treatment performance is that the COD analysis measures wastewater organic matter without regard to its availability to microorganisms. Jenkins and Menar(19) found, for instance, that a nondegradable effluent COD amounting to 15 percent of the influent COD existed for the city of Richmond, California wastewater. At the same time, the contribution of COD contained in effluent suspended solids must be recognized as important in terms of total system performance. For the purposes of this paper, overall COD removal values are included for comparison, because much of the available data relating to the performance of pure-oxygen activated sludge systems is presented in this manner. Overall COD removal for EBBT ranged from 70.7 percent in Run 3 to a high of 87.5 percent in Run 5.

An important factor in the experimental runs conducted with the two-column system was the media carryover rate. While the fine sand employed was the most acceptable of those tested in the preliminary studies, the problem of media carryover was only reduced and not eliminated through its use as the EBBT media. Sand bed depletion did occur in the media selection runs but at a rate lower than with any of the other media under similar conditions. Sand carryover data from Runs 3 through 6 is given in Table 2.

TABLE 2. SUMMARY OF EBBT WET SAND LOSS FOR RUNS 3 THROUGH 6

Run	Column Rise Rate ($l/min/m^2$)*	Wet Sand Loss (kg/day)**	
		Average	Range
3	816	1.86[.68%]	0.45-4.13[1.50%]
4	652.8	0.86[.31%]	0.08-9.53[3.48%]
5	163.2	0.39[.14%]	0.13-1.27[.46%]
6	326.4	1.76[.64%]	0.07-16.80[6.13%]

*1 gpm/ft^2 = 40.8 $l/min/m^2$

**1 lb/day = 0.454 kg/day

[-%] represents daily wet sand loss values expressed as a percent of the total wet sand in the system

Wet sand losses were determined two or three times per week by removing all collected sand from the cone of the system final clarifier. Biological solids were first dislodged from the sand by washing in hot tap water. The excess water was drained away and the remaining sand mixture weighed. Initially, a dry sand weight was also determined. However, because the wet mixture consistently possessed a 21-24 percent moisture content, wet sand weight was considered equally indicative of dry sand carryover performance. In all subsequent experimental runs only wet sand weight is reported.

In general, the rate of sand loss increased with the column rise rate. (with the exception of run 6). The average daily loss rates shown in Table 2 were calculated by dividing the total cumulative wet sand losses for each run by the duration of the run in days. Each run exhibited a similar pattern of sand loss. Reasonable system stability was possible for the first 10 to 20 days of operation. During this period the losses remained below 0.5 kg/day, i.e., less than 0.2 percent of the total system sand weight/day. Then, over a period of 5 to 10 days, the rate of sand loss would increase rapidly, until it reached the maximum values shown in the range column in Table 2. This phenomenon was also accompanied by increasing depths of sand bed expansion, which in some instances resulted in the complete filling of the freeboard space between the top of the bed and the top of the column. The resulting problems of system plugging and loss of microbial mass would force the termination of the experimental run.

A number of techniques were tested to deal with sand losses. In Run 3 the effluent recycle pump was connected to the cone of the final clarifier in an attempt to return carryover sand to the system via the recycle stream. The 7.6 l/min (2 gpm) rate employed, however, was inadequate. The rate was then doubled to 15.2 l/min (4 gpm) in Run 4 and a verticle baffle was installed in the expanded section on column #2 to limit the amount of sand being drawn into the system effluent. The column rise rate was also reduced to 652.8 l/min/m^2 (16 gpm/ft^2). This combination worked effectively until a surge of grease-laden septic tank wastes was discharged into the Lebanon Treatment Plant and subsequently entered the pilot system. The grease coated the sand particles, causing excessive bed expansion and loss of media. The run was terminated.

Subsequently, a skimming ring was installed in the system feed tank to help remove grease and scum before it entered the columns. No further grease problems were encountered.

In spite of continued attempts to recycle sand and the use of various levels of column rise rate, Run 5 and Run 6 also failed to find the operating combination that would prevent excessive sand losses.

Several conclusions based on the operation were made. First, as long as daily sand losses did not exceed 1.0 percent of the total system sand weight (∿2.74 kg/day) reasonably trouble-free process operation was possible. A column rise rate of 652.8 l/min (16 gpm/ft^2) appeared to be the maximum possible rate. Operation at lower rise rates generally extended the length of time the system could operate before the 1.0 percent daily sand loss rate was exceeded. Even the lowest rate employed, 163.2 l/min/m (4 gpm/ft^2), did not prevent eventual rapid and uncontrollable sand losses.

At the completion of Run 6 the operation of the two-column experimental system was halted. Based on the results of the first six runs the decision was made to expand the pilot facilities into a more functional and flexible eight-column system. This system and a summary of its treatment performance are described below:

EXPERIMENTAL RESULTS - EIGHT-COLUMN SYSTEM

System Description

Following the completion of Run 6, construction of an eight-column pilot-scale system was initiated, utilizing the two initial 25.4 cm I.D. (10-inch) acrylic columns and six new PVC columns, which were identical in size to the acrylic columns. The primary purpose of the new design was to increase system flexibility with respect to wastewater retention time, column rise rates, and oxygen addition points. At the same time the plug-flow sequence of eight reactors in series was intended to increase system biological performance and increase the opportunity for nitrification in the final columns of the system. No noticeable nitrification occurred in the first six EBBT runs because of the low wastewater temperatures and because the short duration of the experimental runs did not permit establishment of nitrifiers.

The initial eight-column configuration is shown in Figure 3. Settled wastewater entered the system through the feed tank used previously on the two-column system (not shown here). The skimming ring was retained to protect the system against an influx of grease-laden material and to routinely remove floatables. From the feed tank, wastewater was pumped, as before, into the base of the first column. The two clear acrylic columns were used as the number 5 and number 8 columns with the six new PVC columns placed in the remaining positions. The eight columns were connected in series with 3.8 cm (1.5-inch) diameter PVC pipe which carried liquid from the top of each column to the base of the next. The system was constructed so that any column or columns could be taken off-stream without interrupting overall system operation.

The method of adding oxygen to the system was also modified. The stainless steel diffusers were removed from the two initial columns and they along with the six new columns were fitted with a new type of diffuser. The new diffuser consisted of 3.8 cm (1.5-inch) diameter, 0.79 mm (1/32-inch) thick disk of a flexible plastic material similar to "naugahide". The material has very small pore openings (indistinguishable to the naked eye). This material is used by a local firm in the manufacture of tubular diffusers for use in full scale activated sludge systems. The disk of plastic was sandwiched between two 3.2 mm (1/8-inch) thick rings of plastic used as a support frame. These units were, in turn, secured in a tee at the bottom of the connecting line betwen each column. A diffuser was also added to a tee

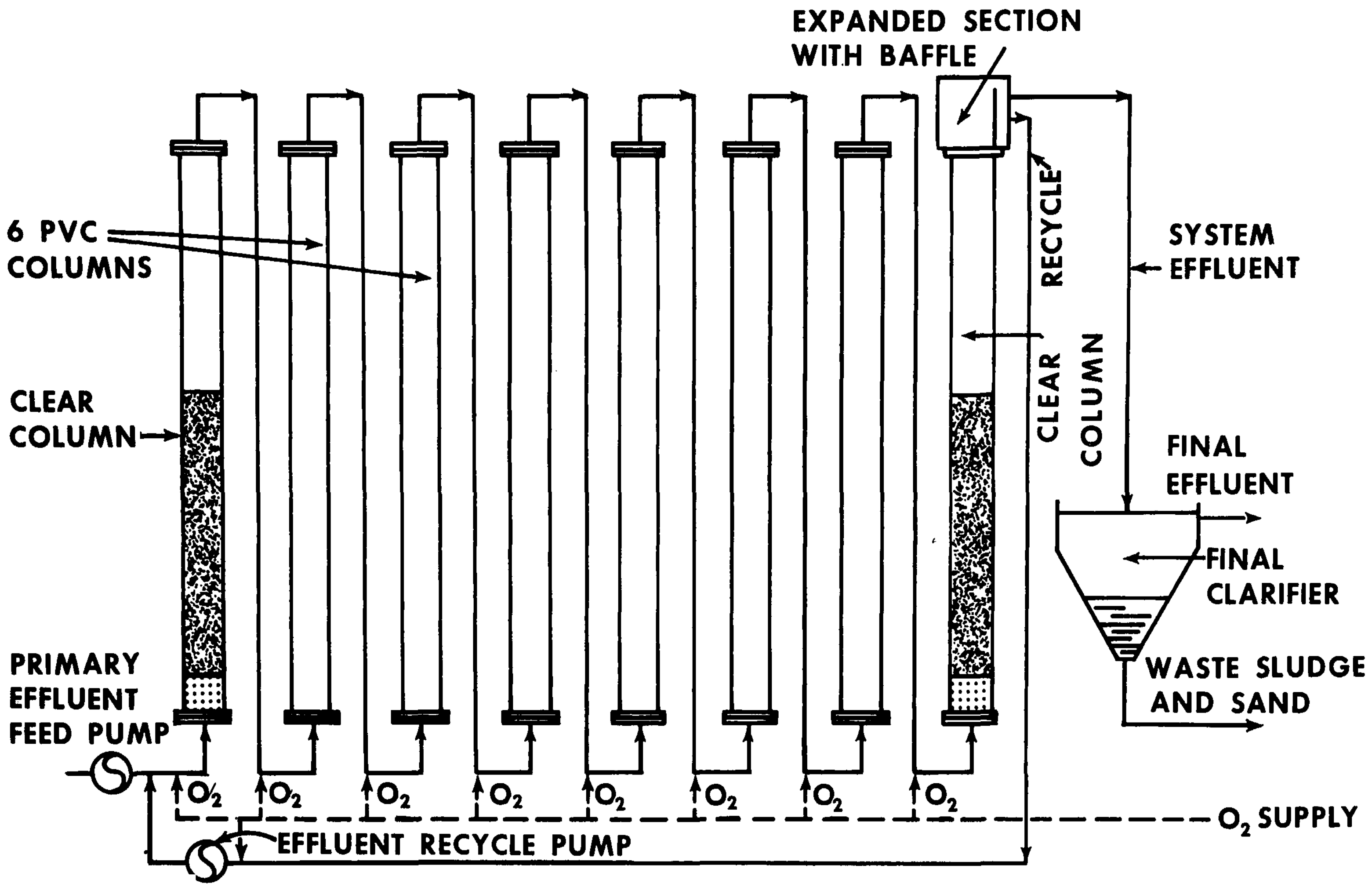

FIGURE 3. EBBT EIGHT COLUMN SYSTEM

on the influent line to the first column. The primary purpose of these changes was to allow the flexibility of step aerating the system, and to offer time for bubble contact with the wastewater prior to its entry into the reactors. At the same time, the plastic diffusers were capable of producing a much finer bubble than the stainless steel diffusers. Over 18 months of continuous use, the plastic material showed no significant deterioration.

From the clear acrylic column in the eighth position, process water was then carried to the original final clarifier. A recycle pump was included to permit sand recirculation from the final clarifier to the first column. The baffled expanded section was allowed to remain on the eighth column initially, but was later removed when it was determined that it did not help control sand loss.

No new provisions were made to attempt to control sand losses from the system. It was anticipated that the greater flexibility of the eight-column system would provide improved operating conditions for sand bed stabilization as well as biological efficiency. At the time of construction, however, no understanding had been reached regarding the true cause of sand loss.

Results

Five experimental runs were conducted on the enlarged system. The first two of these, Run 7 and Run 8, were conducted on the eight-column system in Figure 3. Later runs were conducted on a modified version of this system, which will be described later.

Construction of the enlarged EBBT system was completed in June 1972. Support media and 2.29 meters (7.5 feet) of sand media were placed in each column, leaving an unfluidized free board height of 0.76 meters (2.5 feet). On July 5, the system was started at an influent rate of 16.6 l/min (4.4 gpm). It was found that this system was much more difficult to operate than the initial two-column system. It was a major undertaking to sequentially fluidize the eight columns. Because the PVC columns were opaque the operators could not determine when the sand became properly fluidized. Frequently, lower sections of the bed would apparently fluidize while the top layers would remain intact and rise as a plug as the column filled. If several start-up attempts failed, an access plug at the top of the column was removed and a long, flexible plastic rod was inserted into the column. The rod was worked up and down to break up the sand as the column filled. Once the blocked column was started, the top was resealed and similar steps were taken to start the remaining columns in their numerical sequence. Frequently, more than 46 kg (100 pounds) of sand was lost to the clarifier during the start-up procedure.

Particular attention had to be given to column pressures during both start-up and normal operation. Excessive sand carryover between columns sometimes caused complete plugging of the lines between the columns. The positive displacement feed pump was capable of producing high column pressures in these instances. Under average operating conditions the pressure in the first column was in the range of 146.5 to 171 kg/m^2 (30 to 35 psig). Pressures in succeeding columns decreased linearly down to a value of 19.5 to 29 kg/m^2 (4 to 6 psig) in the last column. Pressures were read from gauges located at the base of each column. Pressures above 195 kg/m^2 (40 psig) generally caused considerable leakage at the flanges on top of the PVC columns and in some cases, when system plugging was rapid, tops even ruptured.

After approximately one week of trial runs and several sand replacements Run 7 was initiated at a feed rate of 30.2 l/min (8 gpm) with no effluent recycle. This provided a calculated liquid retention time of 27.6 minutes, or an actual empty bed retention time of 39.0 minutes. Upon start-up the expanded bed depth in the clear columns was 2.74 m (9 feet), leaving 0.305 m of free board above the bed surface.

The system was operated for two and one-half weeks with minimal sampling while slimes developed on the sand particles. Dissolved oxygen, pH, temperature, and flow rate were the only parameters monitored. Initially, oxygen gas was added only to the first column. An unadjusted rate of 500 cc/minute would maintain dissolved oxygen levels of 1.0 mg/l or greater in all columns. As the biological population developed the rate was increased and oxygen was also applied to additional columns. Sampling to determine waste treatment efficiency was initiated July 25 and continued to August 15, 1972, when Run 8 was started.

In Run 8, the system influent flow rate was reduced to 26.5 l/min (7 gpm) with no effluent recycle. This increased the liquid detention time to 31.5 minutes, or an empty bed detention time of 44.4 minutes. Data were collected under these conditions for 16 days until excessive media loss from the system combined with a weekend power failure forced termination of the run.

The operating conditions and experimental results of Run 7 and Run 8 are summarized in Table 3.

The data show that the treatment efficiency was significantly better than that achieved in previous runs. Average SCOD removal was 71 percent in both runs compared with a previous maximum of 53 percent in Run 5. This likely resulted from several factors including: higher wastewater temperatures; higher soluble waste strength; and an increased degree of fluidization from the doubling of the column rise rate over that of Run 5.

It was discouraging, however, that the increased detention time of Run 8 did not improve treatment efficiency over that of Run 7. While it was possible that the limit of biological degradability of the wastewater had been approached, further analysis revealed that the principle limitation to increased treatment efficiency in Run 8 was the continued inability to control sand media losses from the system. Sand losses for Run 7 and Run 8 are shown in Table 4.

TABLE 3. OPERATIONAL SUMMARY EIGHT-COLUMN SYSTEM

Parameters	Unit	Run 7	Run 8
Waste treated	-	Primary Effluent	Primary Effluent
Influent temperature	°C	20.6	22.1
Influent flow rate (Q)	l/min*	29.9	26.5
Recirculation rate (R)	l/min	0	0
Column rise rate (Q + R/A)	$l/min/m^2$	644.6	571.2
Liquid retention time	min	27.6	31.5
Empty bed retention time	min	39.0	44.4
Final clarifier	$l/min/m^2$	42.2	37.2
Oxygen addition rate (@S.T.P.) (system average)	cc/min gms/m^3***	4508 172	6245 268.8
Dissolved oxygen concentration			
influent	mg/l	1.3	1.0
column No. 1 effluent	mg/l	1.5	2.7
column No. 4 effluent	mg/l	4.4	5.1
column No. 8 effluent (system effluent)	mg/l	5.7	4.2
Performance summary			
Influent TCOD	mg/l	161.5	
Influent SCOD	mg/l	101.0	116.3
Effluent TCOD	mg/l		
Effluent SCOD	mg/l	29.5	33.8
TCOD removal $(\frac{TCODin-TCODout}{TCODin} x\ 100)$	%	-	
SCOD removal $(\frac{SCODin-SCODout}{SCODin} x\ 100)$	%	71	71
Overall COD removal $(\frac{TCODin-SCODout}{TCODin} x\ 100)$	%	81.7	

* l/min x 0.265 gpm
** $l/min/m^2$ x 0.0245 gpm/ft^2
*** gms/m^3 x 0.00835 = lbs/1000 gal.

TABLE 4. SUMMARY OF EBBT SAND LOSS FOR RUN 7 AND RUN 8

Run	Column Rise Rate ($l/min/m^2$)*	Wet Sand Loss (kg/day)** Average	Range
7	644.6	4.82 [.45%]	3.6-7.72 [.72%]
8	571.2	4.15 [.44%]	0.9-7.27 [.77%]

*1 $l/min/m^2$ = 0.0245 gpm/ft^2

**1 kg/day = 2.20 lb/day

The sand loss rates were high throughout both runs. The average daily loss rates of 4.82 kg/day and 4.15 kg/day were more characteristic of the final portions of Runs 3, 4 and 6.

There is little question that the continuous and significant loss of media available to support biological growth affected treatment performance, especially in Run 8. Better than 30 percent of the sand initially in the system was lost by the end of Run 7 and an additional 20 percent was lost by the end of Run 8. In addition to the loss of sand there was also a redistribution of the remaining sand. This can be seen in Figure 4, which indicates the amount of sand remaining in each column where Run 8 was terminated.

Profiles of SCOD removal through the system were compared for Run 7 and Run 8. Data from early in Run 7 (before large cumulative sand loss) indicated first-order removal kinetics. Similar data for the latter portions of Run 8 indicated that little removal was effected in the first two reactors and almost no removal in the third and fourth reactors. The bulk of removal occurred in first-order fashion in the final four reactors. The net effect was reduced overall treatment efficiency, in spite of increased detention time.

At the completion of Run 8, it was apparent that sand bed attrition was the factor most limiting to steady state system operation and the attainment of higher treatment efficiencies. The principle cause of excessive sand loss was believed to be the reduction in particle net density by uncontrolled surface growth of biological slimes. This, in turn, would cause overexpansion of the fluidized bed and loss of coated sand media to the effluent. The fluid shear forces within the reactors were apparently insufficient to effect sloughing of excess biological growth. Sand lost to

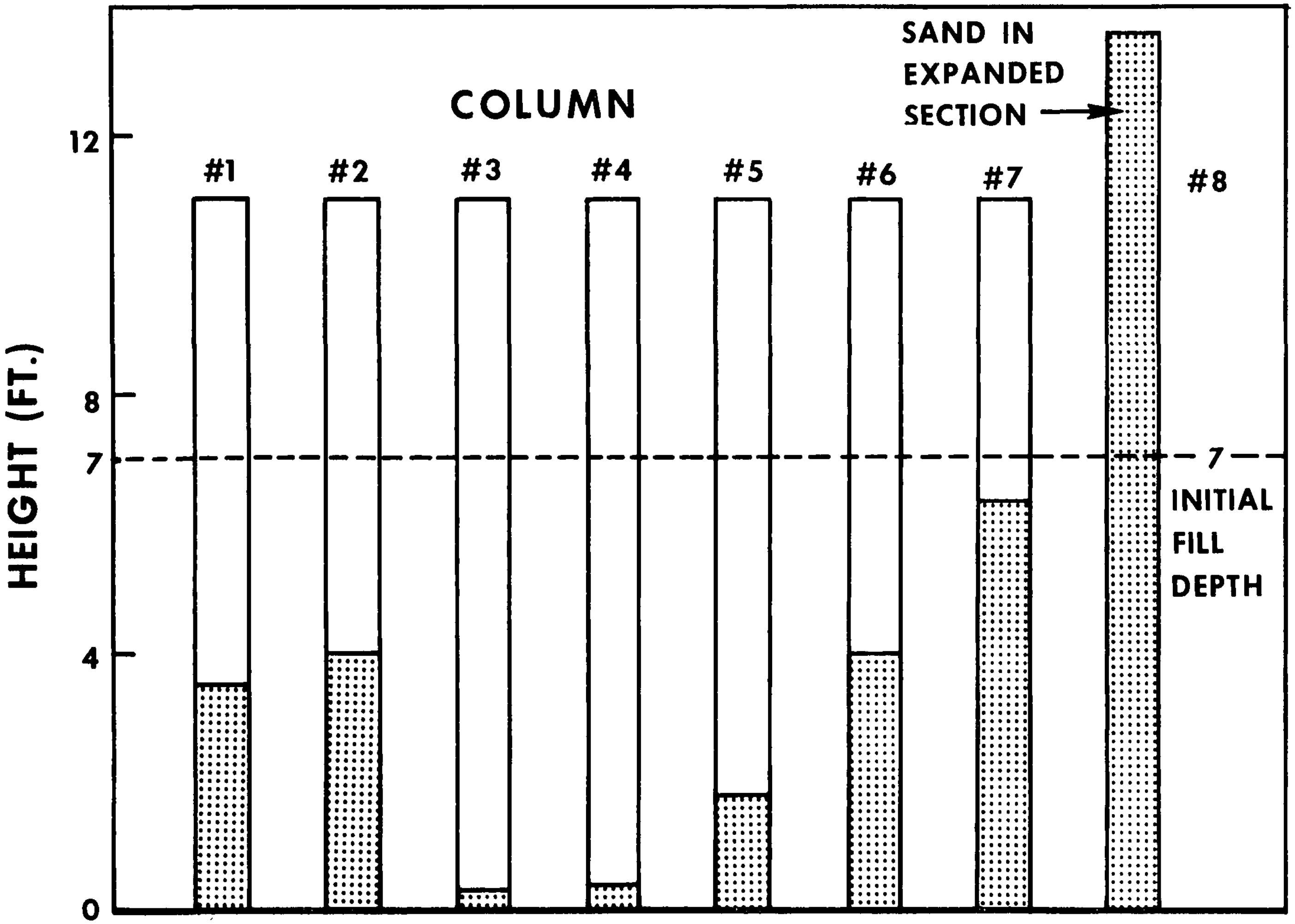

FIGURE 4. COLUMN SETTLED SAND BED DEPTHS AT THE COMPLETION OF RUN 3

the system effluent possessed heavy slime accumulations. Sieve analyses of dried and cleaned samples of carryover sand indicated that sand loss was not specific to any particular particle size. In fact, the size distribution was almost identical to that of the bulk reactor sand.

EXPERIMENTAL RESULTS - MODIFIED EIGHT-COLUMN SYSTEM

Description of Modifications

At the completion of Run 8 a number of system modifications were made to improve control of the fluidized beds. The modified system is shown in Figure 5.

Because the principal objective of this phase of the pilot evaluation was to test biological viability of the process, and not to optimize materials handling considerations, a rather simplistic approach to controlling sand bed depletion was adopted. While it was believed that there was some yet undetermined maximum amount of biological growth that could be supported per sand particle, it was also felt that there was a corresponding maximum degree of sand bed expansion possible for given flow conditions. Consequently, the unfluidized sand bed height was reduced to 1.83 meters (6 feet) in order to provide an additional 0.305 meter (1 foot) of freeboard height.

It was also felt that some artificial means of stripping excess biological growth from the sand would be helpful in controlling sand bed expansion. Unfortunately, the eight column system made any sophisticated control options too expensive and difficult to construct and operate. Pilot plant staff reductions and the demands of other research investigations had also cut system monitoring to one shift per day for only five days per week since the beginning of Run 7. Sand recirculation was therefore chosen as the simplest and most expedient method of maintaining media in the system.

Initially, this was attempted by pumping a dilute slurry of settled sand sludge from the cone of the final clarifier to the base of the first column. This approach worked well, but it was exceptionally hard on the various recycle pumps used. Consequently, a batch sand injection system was adopted. This is diagrammed in Figure 6.

Operationally, carryover or make-up sand was hand charged into the feed cylinder. Then, the incoming waste flow was diverted through the cylinder, fluidizing the sand and carrying it into the lead column just above the gravel support media. When the sand was gone the feed stream was diverted back into the base of the lead column. This method worked well and was employed throughout the remainder of the study.

Additional system changes were made at this time and are diagrammed in Figure 5. One change included the conversion of the skimming tank to a final clarifier. The purpose was to provide a larger settling area and correspondingly lower surface overflow rates than were possible in earlier runs. The smaller clarifier previously used as the final clarifier was converted to an intermediate clarifier for capturing only carryover sand.

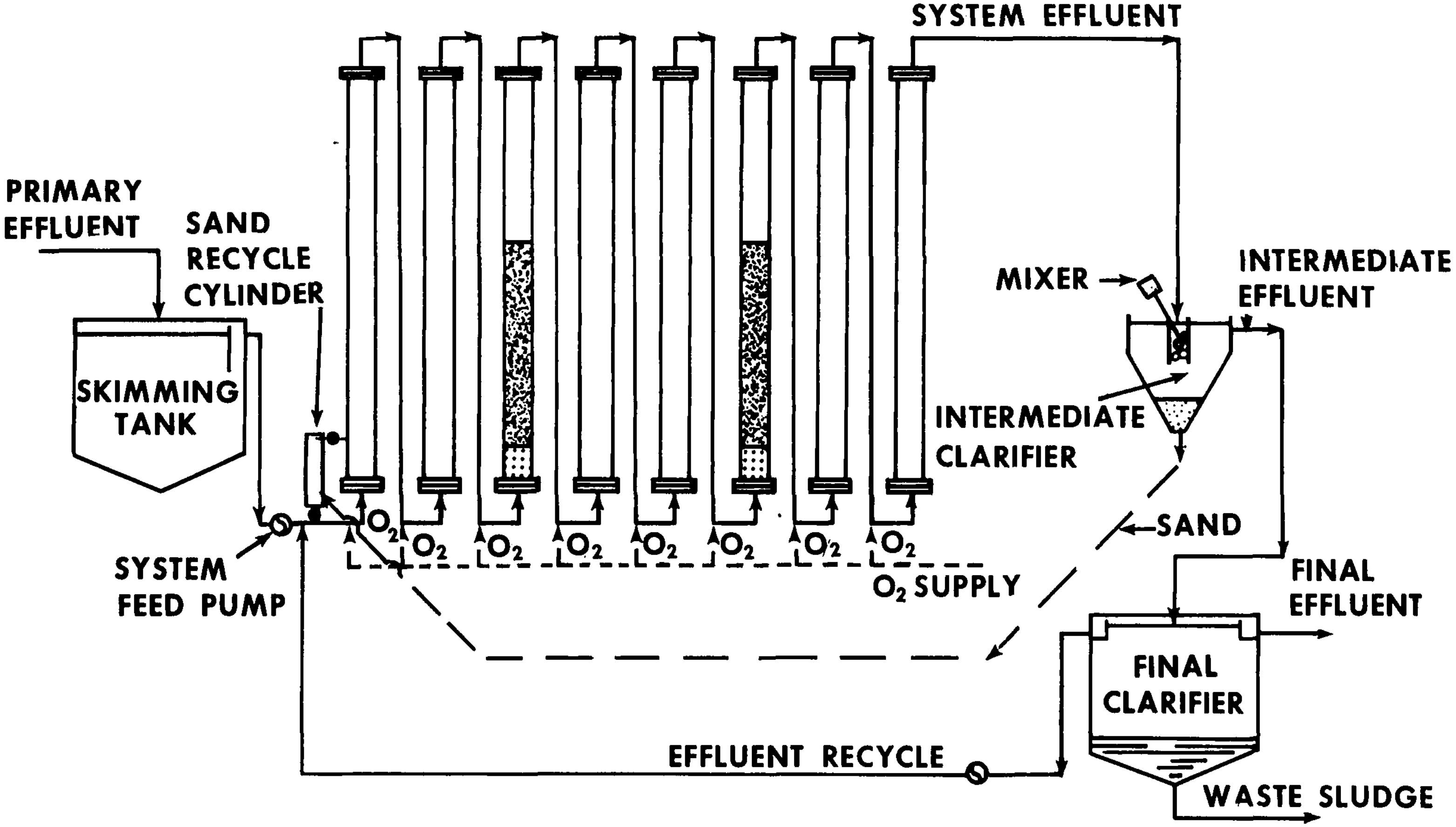

FIGURE 5. MODIFIED EIGHT COLUMN SYSTEM

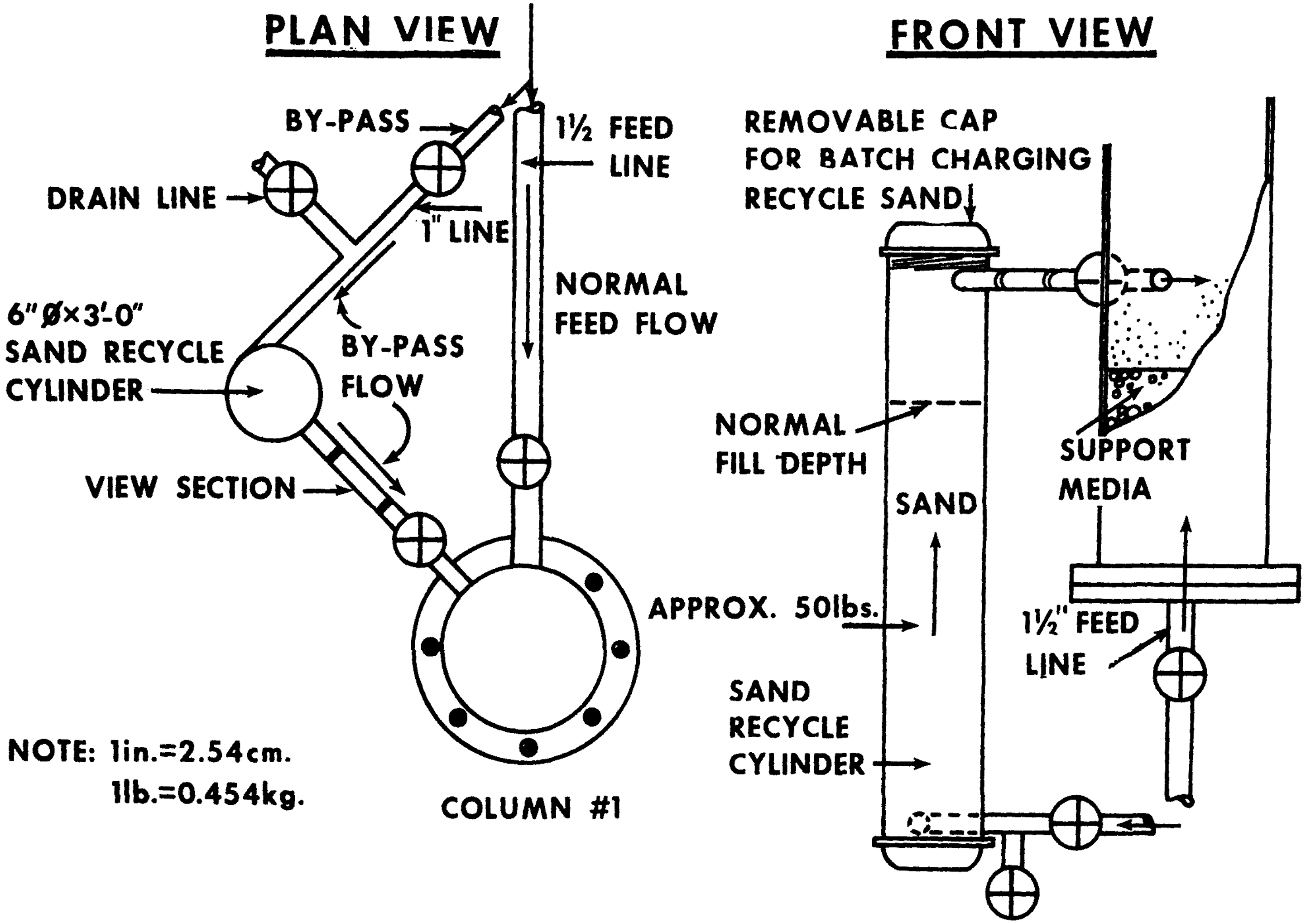

FIGURE 6. SAND RECYCLE SYSTEM

A high-speed laboratory mixer was installed in the clarifier stilling well to shear attached slimes from the passing sand and mix the tank sufficiently to prevent deposition of biological solids which were to be removed in the final clarification step. The modified system also possessed the ability to recycle treated effluent.

To better observe the nature of biological growth and enable visual observations of bed expansion at critical locations in the system, the two clear acrylic columns were moved to the number 3 and number 6 positions in the eight column sequence. The ineffective expanded section was also removed.

Examination of the in-line oxygen diffusers during the shut-down period revealed that the membranes were intact and not clogged. However, it did appear that they had not been operating efficiently during the previous two runs because a significant portion of the oxygen gas had been passing around the circumference of the support disk rather than through the membrane. To correct the problem a new fitting was devised which incorporated a rubber seal to force all gas to pass through the diffuser.

Results

The modified eight-column system was put on stream in early October. Data collection for Run 9 was initiated October 27, under an operating condition of 18.9 l/min (5 gpm) with no recycle. The resulting reactor rise rate of 408 $l/min/m^2$ (10 gpm/ft^2) did not provide adequate bed fluidization. Numerous hydraulic problems developed, one causing a pressure build-up which irreparably fractured one of the clear acrylic columns.

Subsequently, the system was operated with only seven reactor columns and the column rise rate was increased to 571.2 $l/min/m^2$ (14 gpm/ft^2) to provide improved fluidization. A summary of operating conditions for Run 9 is included in Table 5.

Treatment efficiency was quite low, the system achieving only 45.2 percent removal of SCOD, and 51.2 percent removal of TCOD. However, this was principally due to the low wastewater strength entering the system. In spite of low percent removal the soluble effluent quality was better than that in any previous run except Run 7. The relatively high TCOD in the effluent resulted primarily from the washout of solids during the numerous hydraulic upsets of this run.

Sand loss rates during this run were the highest yet experienced. An average of 17.3 kg (38 pounds) of wet sand was lost to the intermediate clarifier daily. This was twice the rate in Run 8 and almost three times the rate of Run 7. Much of the hydraulic difficulty in Run 9 was directly attributable to the high sand loss rate. All sand collected in the intermediate clarifier was weighed daily and charged back into the system.

TABLE 5. OPERATIONAL SUMMARY MODIFIED EIGHT-COLUMN SYSTEM

Parameter	Unit	Run 9	Run 10	Run 11
Waste treated		Primary Effluent	Primary Effluent	Primary Effluent
Influent temperature	^oC	16.4	15	13.7
Influent flow rate (Q)	l/min*	26.5	18.9	18.9
Recirculation rate (R)	l/min	0	7.6	7.6
Column rise rate (Q + R/A)	$l/min/m^2$	571.2	571.2	571.2
Empty-bed retention time	min	44.4	52.0	52.0
Final clarifier S.O.R.	$l/min/m^2$	18.0	12.8	12.8
Oxygen addition rate	cc/min	1140	1256	1601
(system average)	gm/m^3***	49.1	75.7	96.5
Dissolved oxygen concentration				
influent	mg/l	2.2	4.3	3.5
- column No. 1 effluent	mg/l	3.2	5.8	4.6
- column No. 3 effluent	mg/l	5.0	9.2	4.9
column No. 7 effluent	mg/l	4.7	7.2	4.0
Performance Summary				
Influent TCOD	mg/l	157.9	146.1	183.6
SCOD	mg/l	54.6	52.1	82.2
TSS	mg/l			
Effluent TCOD	mg/l	78.0	70.7	101.1
SCOD	mg/l	29.9	26.0	37.3
TSS	mg/l			
TCOD removal $(\frac{TCODin-TCODout}{TCODin}x100)$	%	51.2	5.16	44.9
SCOD removal $(\frac{SCODin-SCODout}{SCODin}x100)$	%	45.2	50.0	54.6
Overall removal $(\frac{TCODin-SCODout}{TCODin}x100)$	%	81.1	82.2	79.7

*l/min x 0.265 = gpm
**$l/min/m^2$ x 0.0245 gpm/ft^2
***g/m^3 x 0.00835 = lbs/1000 gal.

It is important to note that at no time during this run were the sand bed levels in any reactor observed to reach any point above either the free board space sample taps or the column effluent ports. Thus, it was difficult to explain the high sand loss rates.

On December 4, 1972, Run 10 was initiated at an 18.9 l/min (5 gpm) influent rate and a 7.6 l/min (2 gpm) effluent recycle rate. This provided the longest empty-bed retention time yet tested, 52 minutes. As can be seen in Table 5, there was little significant improvement in treatment efficiency over that of Run 9, again largely because of low wastewater strength.

The sand carryover rate was also nearly the same, 17.7 kg (39 pounds) of wet sand per day. However, careful observation of sand bed behavior led to a discovery of what was believed to be another cause of sand bed carryover in the EBBT system. Oxygen gas bubbles rising in the fluidized beds appeared to be causing the bulk of the carryover, rather than excess growth of biological mass on the sand particles. As oxygen bubbles would rise through the fluidized bed sand particles would attach themselves to the bubbles through a surface phenomenon. The sand-encrusted bubbles, about the size of peas, would collect at the top of the fluidized bed. When enough of the sand particles would slough off, the bubbles would rise slowly from the bed surface and pass into the column effluent line, carrying the remaining sand with them.

In order to limit sand transport through this "bubble" mechanism an entrapment device was designed and installed in the top of each column in the system. The device is shown in Figure 7. It consisted of a short length of 7.6 cm (3-inch) diameter PVC pipe installed over the exit opening at the top of each column in the system. The pipe was cut to allow flow passage from the side of the pipe rather than the bottom, which was outfitted with a deflector disk. The function of the ring device was to create a pocket of oxygen gas at the top of each column without interfering with the normal flow of water. Rising gas bubbles with attached sand would collide with the gas-liquid interface at the top of the column, breaking the bubbles and permitting the sand to fall back into the sand bed.

The ring devices were installed in each of the seven columns in the last week of December, while the system was in operation. The effect of these devices was seen rapidly. Within 10 days of continued operation the daily wet sand loss rate fell from 17.7 kg (39 pounds) to 2.7 kg (5.9 pounds). Expressed in terms of percent of total system sand lost per day this represents a decrease from an initial rate of 1.8 percent per day down to 0.34 percent per day.

The changeover to the sand capture devices, completed on December 28, marked the beginning of Run 11. Operation was continued at the same flow conditions employed in Run 10 in order to determine the potential increase in treatment efficiency that could result from improved control of sand carryover. Treatment performance for the one-month period covered by this run is shown in Table 5.

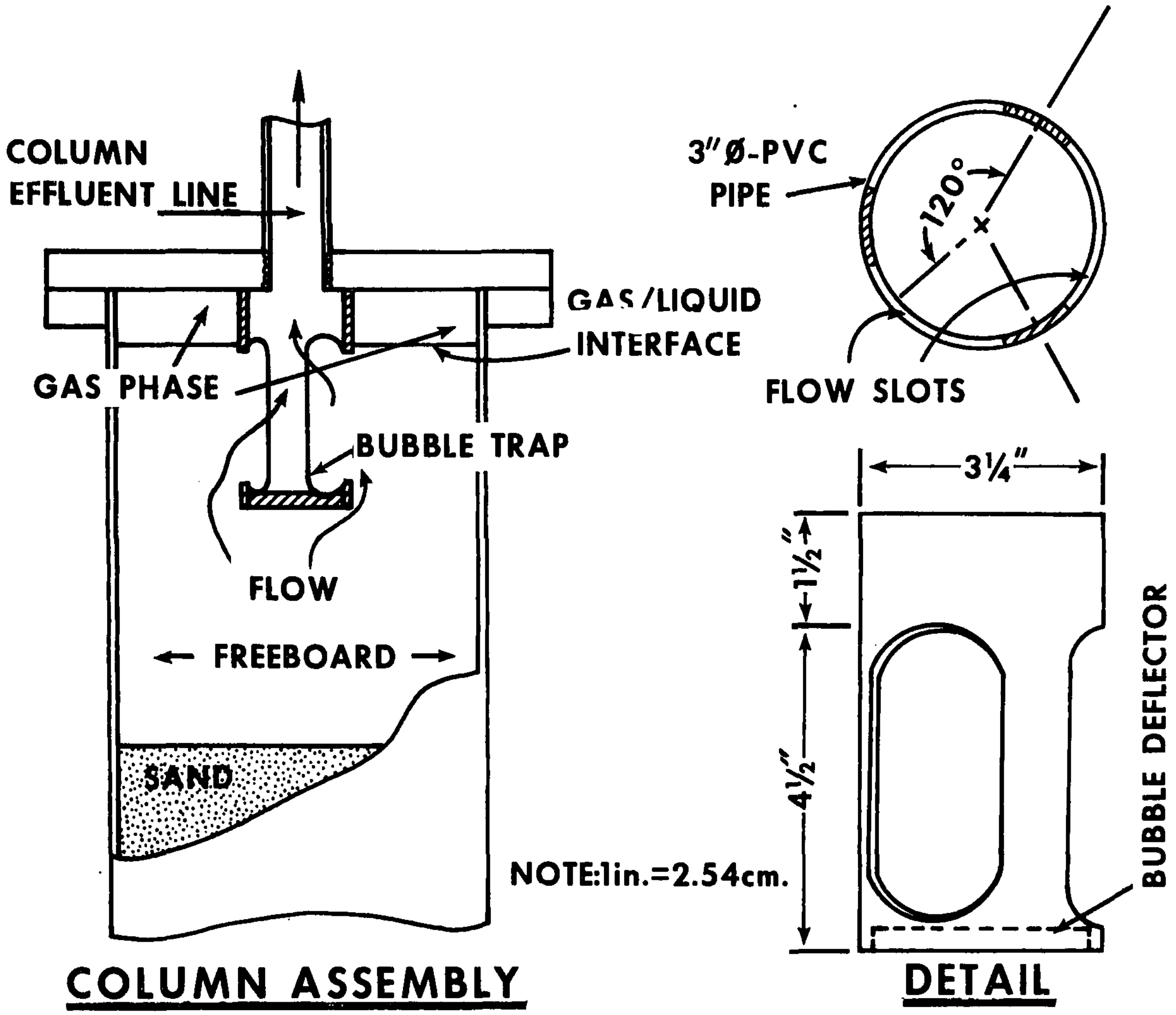

FIGURE 7. EBBT BUBBLE TRAP DEVICE

Treatment efficiency actually declined in Run 11. Also, it was not possible to maintain the low 2.7 kg per day sand loss rate throughout the run. The final two weeks exhibited a slow increase in daily loss rate up to a rate of 4.1 kg per day (9 pounds) on January 22. This increase was accompanied by rising column sand bed heights which reduced the free board space to between 17.8 and 30.5 cm (7 and 12 inches) in each column. Thus, while the sand capture devices had significantly reduced the loss rate, they were only a partial solution. They were not capable of limiting losses due to excess biological growth on the sand particles. At the same time, the increased sand control that was effected did not result in a corresponding improvement in treatment efficiency, at least in the short run.

Based on the results of the eleven runs conducted and a recognition that only five months remained in the study program, the research direction was changed at this point. Three runs (45 days maximum duration) were planned (Runs 12-14). It was felt that reasonable sand bed stability was possible in the short run. All of the planned runs were to utilize the 44-minute empty-bed detention time. Emphasis was switched from hydraulic performance to concentrate on gathering data on mixed liquor suspended solids, waste solids production, and oxygen utilization efficiency. Plans also included "spiking" the system feed stream with digester supernatant to evaluate performance at higher organic loadings.

The results of Runs 12 through 14 are shown in Table 6. It should be pointed out that the system was reduced to six reactors for these runs as a result of the structural failure of the one remaining clear acrylic column at the end of Run 11. Treatment performance, in terms of COD removal, was universally improved over that of Runs 9, 10 and 11. TCOD removal was 5 to 25 percentage points better while SCOD removal rates were 9 to 15 percentage points better. For the most part this appeared to be largely a result of generally higher influent wastewater strengths and temperatures. However, the effluent SCOD concentration was seen to deteriorate somewhat from the values experienced in Runs 9, 10 and 11.

Waste sludge solids production was determined in Run 10 and Run 12 by conducting a mass balance around the system for VSS. For Run 12 an average of 0.33 kg excess VSS was produced per kg of TCOD removed. The system (six columns) average reactor VSS was 12,912 mg/l. The calculated solids retention time (SRT) was 8.06 days. Run 14, which suffered considerably from excessive sand loss problems, exhibited a nearly two-fold increase in excess solids production, 0.527 kg VSS per kg TCOD removed. The reactor VSS concentration was 14,863 mg/l and the SRT was 5.2 days, significantly lower than that in Run 10.

The reactors were very stable with regard to sand loss rates in Run 12 and Run 13. Overexpansion of the sand beds did not become prevalent until the end of Run 13. Run 14, however, exhibited very poor stability with the average daily loss exceeding 4 percent of the system total wet sand. Table 7 summarizes sand loss parameters for these three runs.

TABLE 6. OPERATIONAL SUMMARY - SIX-COLUMN SYSTEM

Parameter	Unit			
Waste treated		Primary Effluent	Primary Effluent	Primary Effluent
Influent temperature	°C	12.1	12.5	14.5
Influent flow rate (Q)	l/min*	18.9	18.9	18.9
Recirculation rate (R)	l/min	0	0	0
Column rise rate	$l/min/m^2$	408	408	408
Empty-bed retention time (Q)	min	44.1	44.1	44.1
Final clarifier S.O.R.	$l/min/m^2$	12.8	12.8	12.8
Oxygen addition rate (system average)	cc/min gm/m^3***	1744 105.1	2408 145.3	3138 189.2
Dissolved oxygen concentration				
Influent	mg/l	6.0	4.3	3.4
Column No. 1 effluent	mg/l	5.6	3.1	4.1
Column No. 3 effluent	mg/l	5.4	6.8	11.1
Column No. 6 effluent	mg/l	6.8	10.4	13.0
Performance Summary				
Influent TCOD	mg/l	195.5	201.6	170.7
Influent SCOD	mg/l	83.1	131.6	114.7
Influent TSS	mg/l	86.5	-	-
Effluent TCOD	mg/l	85.1	75.1	56.0
Effluent SCOD	mg/l	36.7	53.4	34.8
Effluent TSS	mg/l	32.4	-	
TCOD removal $(\frac{TCODin-TCODout}{TCODin} x100)$	%	56.5	62.7	67.2
SCOD removal $(\frac{SCODin-SCODout}{SCODin} x100)$	%	55.8	59.4	69.7
Overall removal $(\frac{TCODin-SCODout}{TCODin} x100)$	%	81.2	73.5	79.6
TSS removal $(\frac{TSSin-TSSout}{TSSin} x100)$	%	67.5	-	-

*l/min x 0.265 = gpm
**$l/min/m^2$ x 0.0245 = gpm/ft^2
***gm/m^3 x 0.00835 = lbs/1000 gal.

TABLE 7. SUMMARY OF EBBT SAND LOSS FOR RUNS 12, 13, and 14

Run	Column Rise Rate ($l/min/m^2$)	Wet Sand Loss(kg/day) Average	Wet Sand Loss(kg/day) Range	Avg. % of Total System Sand/Day
12	408	4.1	0.45-20.4	0.6
13	408	7.7	2.3-22.7	1.13
14	408	27.5	12.1-49.9	4.03

$l/min/m^2 \times 0.245 = gpm/ft^2$

kg/day x 2.20 = lb/day

The high loss rates of Run 14 were believed to have resulted from the "spiking" of the system influent with digester supernatant in Run 13. A short time after supernatant addition was started a significant shift occurred in the microbiological population on the sand in the reactors. Spaerotilus and Thiothrix began to predominate. A phenomenon similar to "bulking" in conventional activated sludge plants resulted in a rapid increase in the degree of sand bed expansion and daily loss rates. Since this had not happened in previous testing it was felt that some component of the digester supernatant had encouraged the proliferation of the filamentous growths.

As a consequence of the uncontrollable sand losses in Run 14, data collection was stopped. Digester supernatant addition was also terminated. The six-column system was operated on a tap water feed for two weeks to reduce the filamentous population. During this time a number of modifications were made to prepare for the final test period, Run 15, which was to include further monitoring of excess solids production as well as a determination of oxygen utilization efficiency.

In order to more accurately monitor dissolved oxygen levels in the system a Weston and Stack model 3000 Dissolved Oxygen Analyzer and a model 60 high pressure/high dissolved oxygen concentration probe were added. A limitation of past dissolved oxygen determinations was that samples taken from the pressurized system had to be analyzed at atmospheric pressure with a bench D.O. meter. The new system was fed by a sampling manifold connected into the freeboard space of each of the six columns. By opening the appropriate valves a sample could be withdrawn from each column and passed directly into the D.O. probe at the same pressure that existed in the column. Dissolved oxygen levels measured in this way were on the average 1.0 mg/l higher than identical determinations made with a bench meter at atmospheric pressure.

An off-gas collection system was also added. The stilling well of the intermediate clarifier was capped and equipped with a gas collection line. The volume of off-gases was measured with a wet test meter. The exhaust from the meter was collected in $0.0283m^3$ ($1\ ft^3$)mylar gas collection bags and regularly analyzed for O_2, N_2, and CO_2 gas concentration.

Wastewater feeding was instituted on May 31. The start-up period suffered from numerous plugging problems which were a result of five separate City of Lebanon power failures. Stability was finally achieved by mid-July and preliminary sampling was started July 17. The final run, Run 15, was instituted August 13 when the biological performance reached equilibrium. A summary of performance from this point to the final day of operation, September 10, appears in Table 8.

This was one of the most stable periods of the entire experimental program. TCOD removal efficiency was 75 percent and SCOD removal efficiency averaged 55.9 percent. The effluent TCOD of 48.8 mg/l was also the best obtained by the EBBT system. The effluent TSS concentration was 11 mg/l. Sand bed performance was exceptionally stable throughout the entire test period. The average daily loss to the intermediate clarifier was 2.95 kg/day (6.5 lbs/day). The unit was free of plugging and associated hydraulic problems.

During the period covered by Table 8 data, the average effective MLVSS was 14,276 mg/l. Solids production data indicated that 0.26 kg excess volatile solids was formed per day per kg of TCOD removed. Based on the average MLVSS maintained this was equivalent to 0.115 kg excess VSS formed/day/kg MLVSS, and 0.422 kg TCOD removed/day/kg MLVSS. The SRT was 8.7 days.

At the completion of Run 15 the EBBT study was terminated. The significance of the operating results obtained from the 3 year study and conclusions regarding the feasibility of the EBBT process are discussed in the following section.

TABLE 8. OPERATIONAL SUMMARY SIX-COLUMN EBBT SYSTEM

Parameter	Unit	Run 15
Waste treated		Primary Effluent
Influent temperature	°C	22.1
Influent flow rate (Q)	l/min*	18.9
Recycle rate (R)	l/min	0
Column rise rate (Q + R/A)	$l/min/m^2$**	408
Empty bed retention time	min	44.1
Final clarifier S.O.R.	$l/min/m^2$	453
Oxygen addition rate	cc/min	3438
(system average)	gm/m^3***	147.3
Dissolved oxygen concentration		
influent	mg/l	1.7
- column No. 1 effluent	mg/l	5.4
- column No. 3 effluent	mg/l	13.4
- column No. 6 effluent	mg/l	11.9
Performance Summary		
Influent TCOD	mg/l	196.3
SCOD	mg/l	73.7
TSS	mg/l	85.2
Effluent TCOD	mg/l	48.8
SCOD	mg/l	32.4
TSS	mg/l	11.0
TCOD removal $(\frac{\text{TCODin-TCODout}}{\text{TCODin}} \text{x100})$	%	75
SCOD removal $(\frac{\text{SCODin-SCODout}}{\text{SCODin}} \text{x100})$	%	55.9
Overall removal $(\frac{\text{TCODin-SCODout}}{\text{TCODin}} \text{x100})$	%	83.5
TSS removal $(\frac{\text{TSSin-TSSout}}{\text{TSSin}} \text{x100})$	%	87

*l/min x 0.265 = gpm

**$l/min/m^2$ x 0.0245 = gpm/ft^2

***gm/m^3 x 0.00835 = lb/1000 gal.

SECTION 6

DISCUSSION

TREATMENT PERFORMANCE

Carbonaceous Treatment

A principal objective of the EBBT pilot-scale investigations was to determine the system operating conditions which would maximize biological treatment efficiency. The primary system control parameter in this regard was the hydraulic retention time. To a lesser extent reactor dissolved oxygen levels could be varied to alter system conditions. The solids retention time was not purposely controlled at a set level. Rather it was derived from biological solids wasting through two mechanisms: 1) natural sloughing of biological slimes from sand particles in the reactors; and, 2) mechanical shearing of excess growth from carryover sand either by force of a sand recycle pump or by a high-speed mixer.

On the basis of average treatment performance data from each of the experimental runs an effort was made to determine the relationship between COD removal efficiency and empty-bed retention time. Little correlation was found between TCOD removal efficiency

$$\left(\frac{\text{TCODin} - \text{TCODout}}{\text{TCODin}} \times 100\right)$$

and empty-bed retention time because of the random nature of TCOD removal data. To a great extent this was caused by the considerable range of surface overflow conditions under which the final clarifiers were operated. The numerous system modifications also introduced variability to clarifier performance. Most importantly, TCOD removal efficiency appeared to be closely tied to the degree of hydraulic stability in the sand beds. Runs with high sand loss rates consistently produced final effluents high in TCOD because of the increased sloughing of surface slimes and the resulting increase in solids applied to the clarifier.

A relationship was determined for SCOD removal efficiency as a function of empty-bed retention time. This is illustrated in Figure 8. Performance was found to fall into two separate regimes based upon influent wastewater temperatures. As would be expected greater removal efficiencies were possible at the higher temperatures ($>18^{\circ}$C). A maximum removal efficiency of 71 percent was achieved at the higher temperatures at an empty-bed retention of time of 44 minutes. In the lower operating temperatures

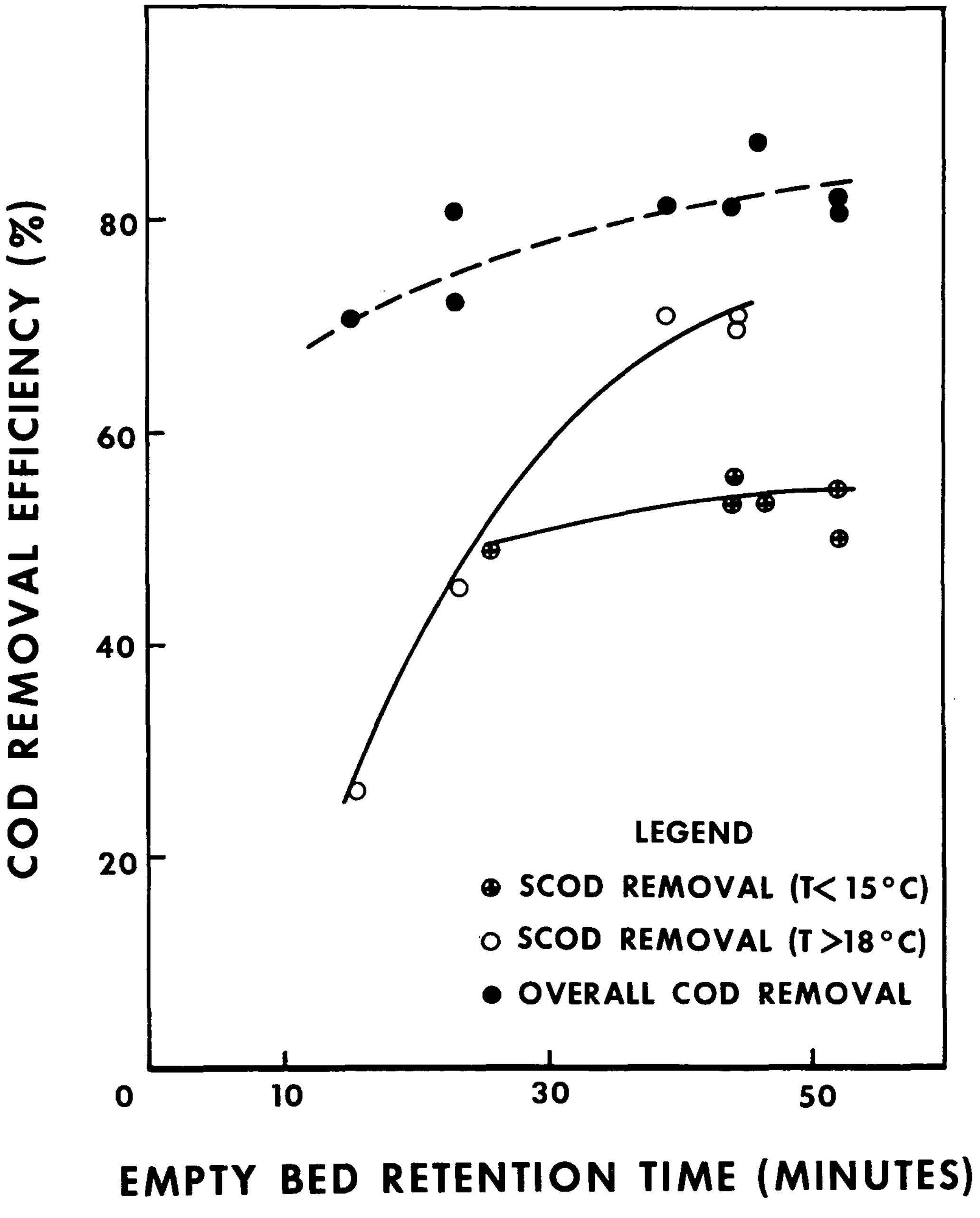

FIGURE 8. COD REMOVAL EFFICIENCY AS A FUNCTION OF EMPTY BED RETENTION TIME

range, soluble COD removal did not exceed 55 percent, even at retention times in excess of 50 minutes. This resulted from the combined effects of lower reaction rate and the generally weaker influent waste strength during the colder months of operation.

Also shown in Figure 8 is the relationship between overall COD removal

$$\left(\frac{\text{TCODin - SCODout}}{\text{TCODin}} \times 100\right)$$

and empty-bed retention time. The curve indicates that a maximum overall COD removal efficiency of 85 percent was approached at an empty-bed detention time of 52 minutes.

EBBT treatment performance was also examined in terms of the volumetric organic loading rate applied to the system, expressed as kg of COD applied per day per m^3 of reactor volume. The rates during pilot testing ranged from 4.99 kg COD/day/m^3 to 35.2 kg COD/day/m^3 (312 lb COD/day/1000 ft^3 to 2200 kg COD/day/1000 ft^3). In all cases the empty-bed reactor volume was employed in the calculations.

The relationship between COD removal efficiency and the COD loading rate which was determined for the EBBT system is shown in Figures 9 and 10 where TCOD removal (%) and SCOD removal (%) are respectively plotted against their corresponding volumetric loading rates. In both instances the effect of low influent wastewater temperature and strength is apparent. The data appeared again to separate into two groups, the upper curve in each figure representing data collected at wastewater temperatures above 18°C and the lower curve that collected at temperatures below 15°C. However, when absolute effluent quality (based on total and soluble COD) was examined as a function of the volumetric loading rate, no temperature differentiation was possible. This may be seen from Figures 11 and 12, where effluent TCOD and SCOD are plotted respectively against the TCOD and SCOD volumetric loading rate. It appears that lower influent waste strengths in the colder months had a greater effect upon COD removal efficiency than the lower wastewater temperatures. In more typical wastewaters possessing higher waste strengths, however, it is believed that the temperature effects would predominate. At Lebanon, treatment efficiency calculations were sometimes limited mathematically by the strength of the wastewater treated.

The curve in Figure 11 suggests that the relationship between effluent TCOD and the TCOD volumetric loading rate is linear up to a rate of approximately 8 kg TCOD/day/m^3 (500 lb TCOD/day/100 ft^3), after which an apparent first-order relationship prevails. At this high (in comparison with conventional activated sludge systems) rate the system produced an average effluent quality of 96 mg/l TCOD, 41 mg/l SCOD, and a calculated average $TBOD_5$ of 27.6 mg/l (based on an effluent TCOD:$TBOD_5$ ratio of 3.48).

One of the principle objectives of the pilot-scale studies at the Lebanon Pilot Plant was to determine the optimum design operation conditions for the EBBT process. Based upon the biological treatment performance data collected the pilot scale system operated most consistently

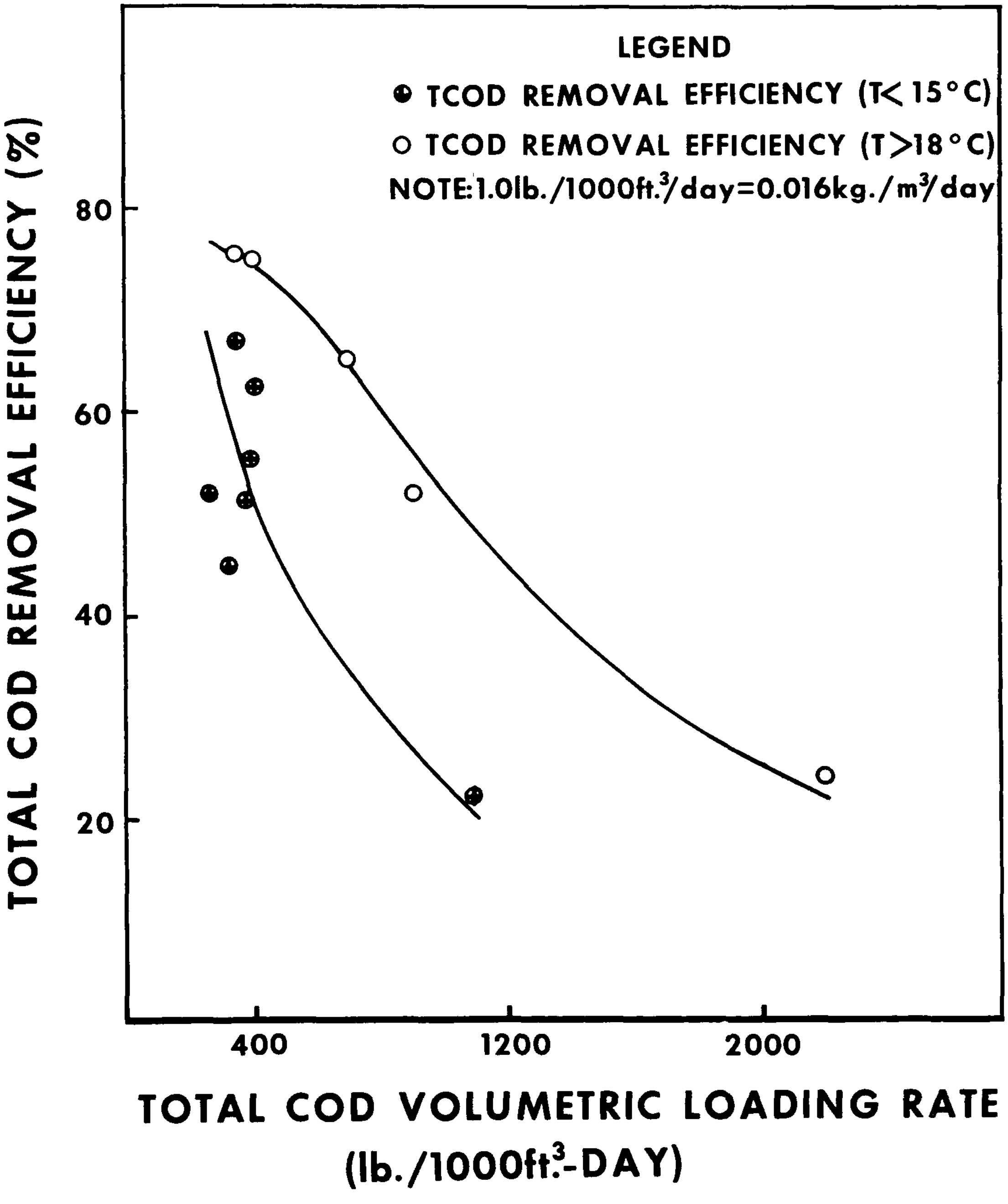

FIGURE 9. TCOD REMOVAL EFFICIENCY AS A FUNCTION OF TCOD VOLUMETRIC LOADING RATE

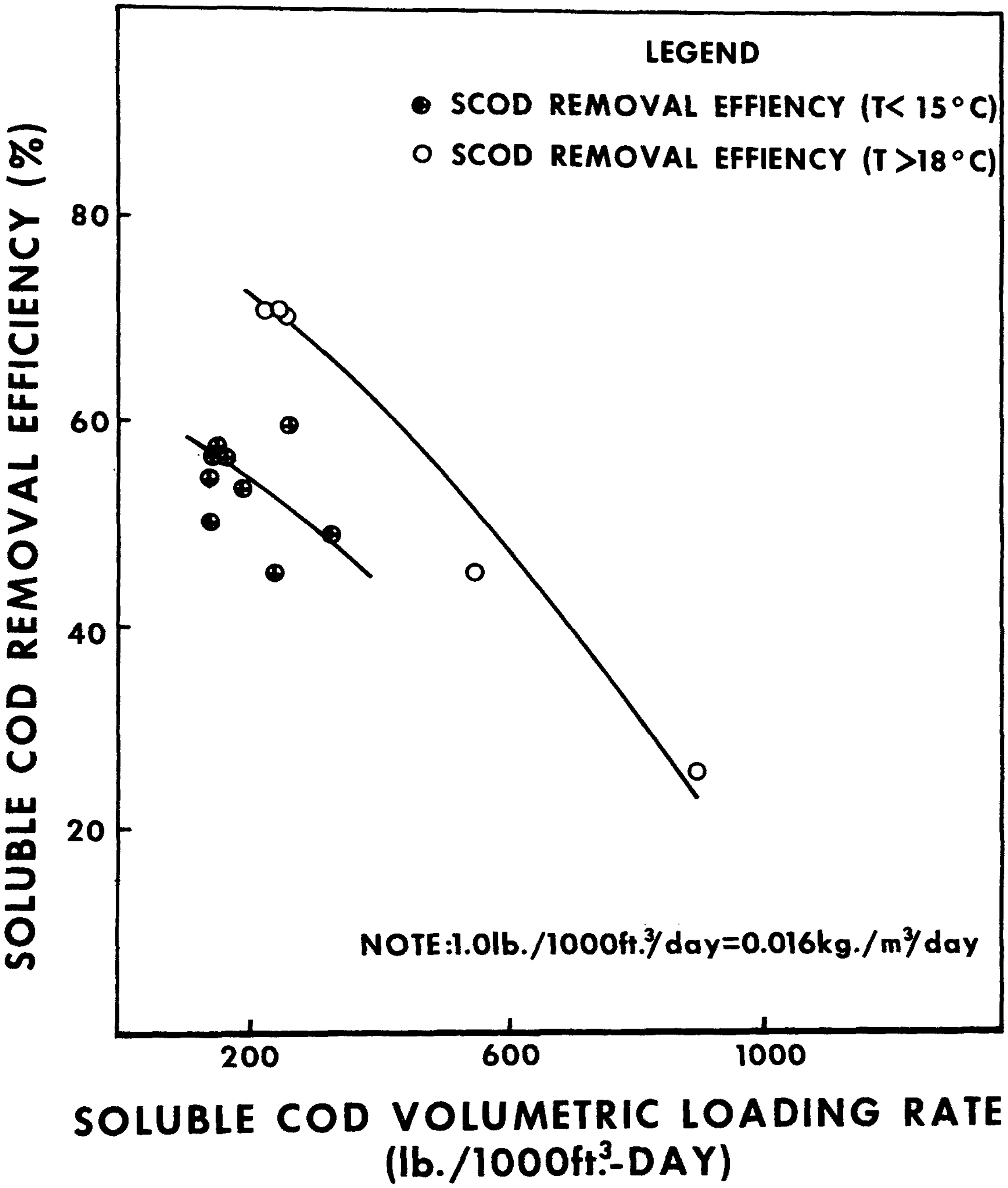

FIGURE 10. SCOD REMOVAL EFFICIENCY AS A FUNCTION OF SCOD VOLUMETRIC LOADING RATE

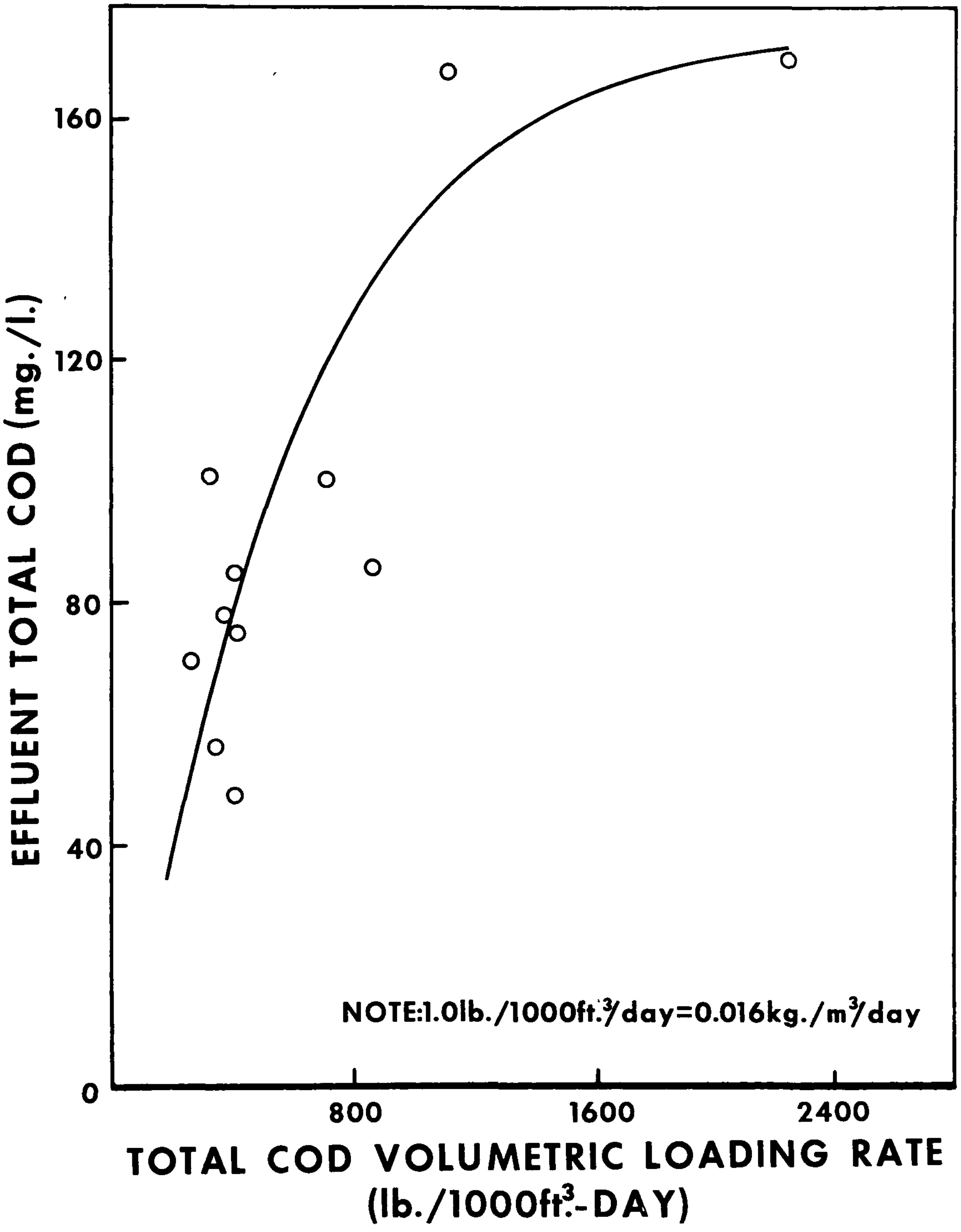

FIGURE 11. EFFLUENT TCOD AS A FUNCTION OF TCOD VOLUMETRIC LOADING RATE

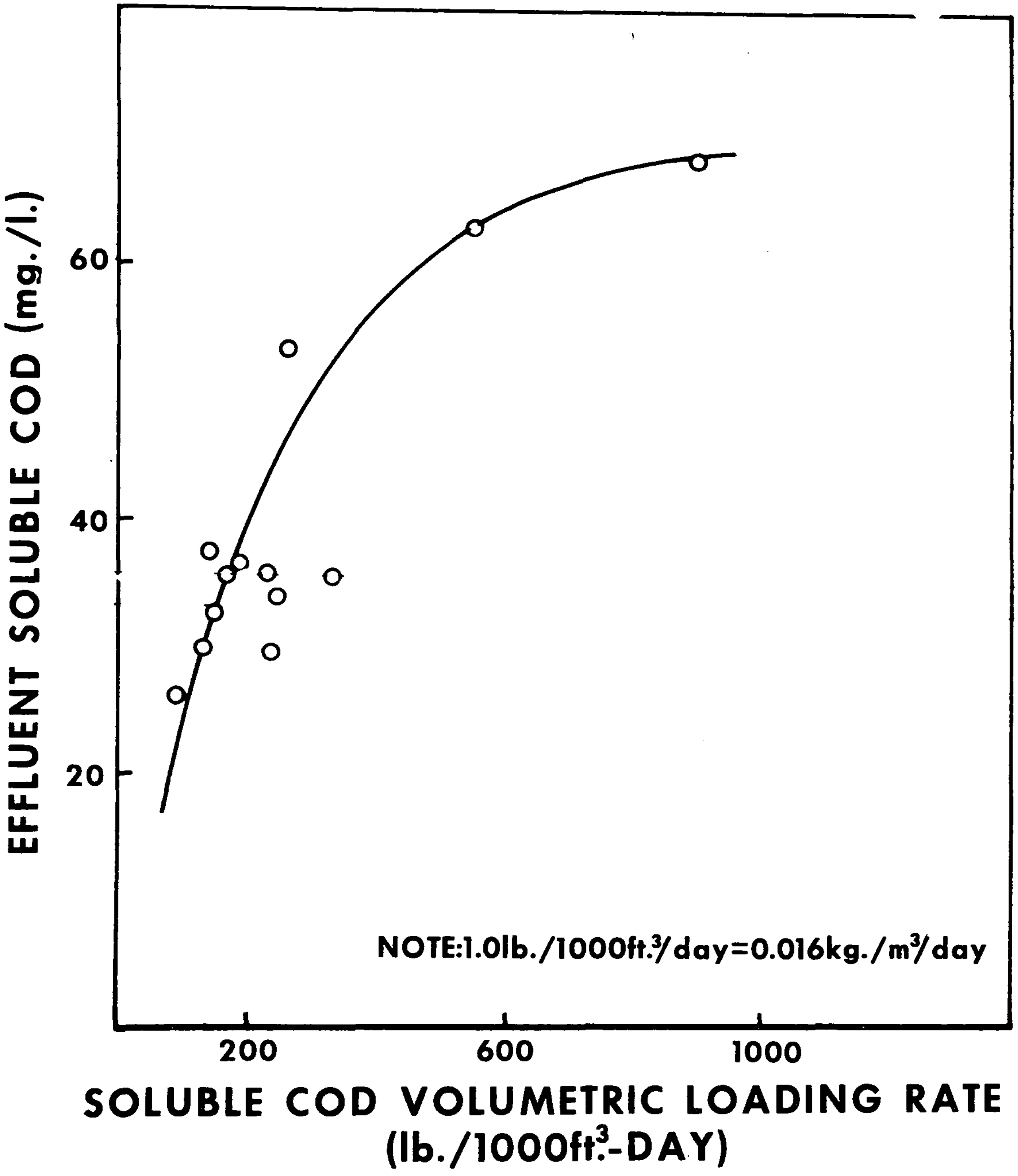

FIGURE 12. EFFLUENT SCOD AS A FUNCTION OF SCOD VOLUMETRIC LOADING RATE

under the following conditions:

empty-bed retention time:	44 minutes (Q)
reactor rise rate:	408 $1/\text{min}/\text{m}^2$
TCOD volumetric loading rate:	6.4 $\text{kg}/\text{day}/\text{m}^3$

Under these conditions an average effluent quality of 80 mg/l TCOD and 31 mg/l SCOD was obtained. This corresponded to a calculated average effluent TBOD_5 of 23 mg/l.

It is not possible, however, to suggest that these necessarily represent optimum conditions, due to the physical limitations of the pilot system itself. Many of the complications encountered with the operation of the multi-column system have been discussed, including sand bed stability, dissolved oxygen control, and plugging. Each of these contributed to the problem of maintaining or sometimes even achieving stable operating conditions. In all cases, however, data from period of extensive system upset were not used in the determination of average system performance.

In summary, the biological treatment performance of the EBBT pilot system indicated that under stable operating conditions a high-quality effluent could be produced at significantly higher waste loading rates and shorter hydraulic retention time than the conventional activated sludge systems. These results are encouraging, in light of the physical limitations of the pilot test system, and indicate that the process could be feasible for eventual full-scale application. However, optimum operating conditions cannot be defined until the process is evaluated on stronger wastewater and with improved methods of dissolved oxygen supply and sand bed control.

Nitrification

Ammonia and nitrate data were collected at a number of points during the EBBT test program. The degree of ammonia oxidation was slight to moderate and no consistent pattern of nitrification was experienced upon which quantifiable conclusions could be drawn. It is believed that transport of sand through and out of the pilot system prevented the establishment of a stable population of nitrifiers.

SOLIDS PRODUCTION

One possible benefit from the use of commercial oxygen in biological treatment processes is a decrease in sludge production (yield) as compared with conventional air activated biological processes. One hope in the EBBT investigations was that even lower yields could be obtained by employing commercial oxygen in a fixed film system.

Much attention has been devoted to determining the effect of dissolved oxygen concentration on microbial yield. There is considerable disagreement among researchers as to what the true effect is. Some have indicated that there is a significantly decreased yield with oxygen aeration when compared to air aeration under identical conditions (15, 21, 24), while others have concluded that there is either no effect or that the reported differences are caused by modified SRT values rather than direct oxygen effects (22, 23).

In one study comparing bench-scale air and oxygen activated sludge systems, the high dissolved oxygen concentrations of the oxygen reactor resulted in a 20 percent reduction in yield when compared to the air reactors (24). Suspended growth and attached film biological reactors were also compared. The yields in both the air and oxygen attached film systems were lower than those obtained with the corresponding suspended growth systems (11 percent for air and 24 percent for oxygen).

For the EBBT system, sludge production, or yield, was determined for Runs 12, 14, and 15. Yield was determined by measuring the amount of sludge wasted plus the amount of solids lost to the effluent over a given time period and relating this to a specific organic loading condition. Because in EBBT there was no sludge recycle, all sludge collected in the final clarifier was waste sludge. The results of these runs are summarized in Table 9.

TABLE 9. SUMMARY OF EBBT SOLIDS PRODUCTION DATA

Parameter	Run 12	Run 14	Run 15
kg TCOD removed/day	2.90	3.30	3.58
kg excess VSS formed/day	0.95	1.69	0.98
kg MLVSS (system average)	7.67	8.83	8.49
$\frac{\text{kg excess VSS formed/day}}{\text{kg TCOD removed/day}}$	0.33	0.53	0.26
$\frac{\text{kg excess VSS formed/day}}{\text{kg MLVSS}}$	0.38	0.38	0.42
SRT (days)	8.06	5.20	8.70
MLVSS (mg/l) (system average)	12,912	14,863	14,276
Average wet sand loss (kg/day)	4.1	27.5	2.95
Dissolved Oxygen (mg/l)			
Influent	6.0	3.5	1.7
Column #1 effluent	5.6	4.1	5.4
Column #3 effluent	5.4	11.1	13.4
Column #6 effluent	6.8	13.0	11.9

The average rate of TCOD removal in terms of kg per day was seen to increase with successive runs. This primarily resulted from the increase in influent waste strength from spring (Run 12) to late summer (Run 15). The average daily excess volatile solids formation was nearly identical in Run 12 and Run 15, but Run 14 was significantly higher. As a consequence the yield value for Run 14 was also higher than that for the other runs. The yield was 0.55 kg VSS formed/day/m^3 versus values of 0.26 and 0.33 kg VSS formed/day/m^3 experienced in Run 12 and Run 15.

The principal reason for the high yield in Run 14 was the high sand loss rate (27.5 kg/day) caused by the proliferation of filamentous microorganisms. This resulted in the transport of much greater amounts of sand surface-bound slimes from the reactors. These were sheared from the sand in the intermediate clarifier and settled as waste sludge in the final clarifier. The average system MLVSS decreased from 16,000 mg/l at the start of the run to 13,500 mg/l at the end. Thus, the apparent high solids production of this run was principally a result of unstable sand bed conditions. MLVSS values were reasonably constant in the other two runs.

The yield values for the EBBT pilot system were essentially comparable to those reported for suspended growth high-purity oxygen systems. The significant reductions in waste sludge production rates postulated in the beginning phases of the program were not experienced.

It is also important to note at this point that a considerable amount of effort was involved in actually determining average MLVSS for the entire system. First of all, a determination had to be made for each of the reactors because the amount of biological growth per sand particle varied with location in the system. Also, there was only one sample point in each column from which a grab sample of the fluidized bed could be taken. The was located at the approximate midpoint of the height of the bed when expanded at a rise rate of 10 gpm/ft^2. This was assumed to be representative of conditions in the entire bed. An obvious difficulty here is apparent when one considers the known variation in the height of sand in each column. One day the sample point might be at the midpoint of the bed, while later in the week it would be perhaps at the one-third or two-thirds point. The actual determination of the volatile solids concentration on the bed sample was also complicated. Typically, a 2000 ml sample was drawn from each column. In exiting the sample tap some sludge solids were stripped from the sand particles. Thus, VSS had to be determined for both the free solids and the attached solids. A total mass of volatile solids was determined for each sample and then the total divided into the total volume of the initial sample to determine the effective concentration of MLVSS. Ideally, the best practice would have provided for a series of sample points in each column so that a sample composited with height could be obtained. In general, however, the values for MLVSS obtained with the mid-column sampling method proved consistent. They are felt to be representative of the actual volatile solids content in the system. The value of MLVSS used in computing excess sludge production was the average of all total system values.

Some concept of the distribution of MLVSS in the EBBT process in terms of time and system location can be gained from an examination of

Table 10. This displays data employed in the determination of system MLVSS for Run 15. Throughout the run the mixed liquor volatile solids concentration was consistently lowest in the initial column stages and highest in the final stages. To some extent this pattern resulted from the distribution of sand in the system. Transport of sand between columns generally caused sand to collect in the final columns in the system flow sequence. Examination of SCOD removal with time, however, revealed that the majority of treatment was still occurring in the first two columns. On the average, over 70 percent of the SCOD removal was achieved in the first two columns.

OXYGEN UTILIZATION

A limitation of the EBBT experimental system was the inability to precisely control dissolved oxygen levels in the reactors. Oxygen gas was fed to each reactor through a separate rotameter. The oxygen gas was supplied by several 113.5 kg (250 pound) liquid oxygen cylinders connected in parallel. The gas supply was regulated to 195.3 kg/m^2 (40 psig) prior to entering the rotameters.

The dissolved oxygen control strategy was essentially to maintain the average system dissolved oxygen concentration at high levels. The hope here was to encourage oxygen penetration into the attached slime layers, and to minimize excess sludge production. The maximum concentration employed, however, was generally limited to below 10 mg/l, because the higher oxygen addition rates resulted in exceptional bubble transport through the reactors, causing buildup in the reactors.

While it was generally possible to maintain adequate dissolved oxygen levels in the system reactors, it was difficult to maintain consistent levels. Reactor dissolved oxygen concentrations varied widely and unpredictably from day to day and sometimes from morning to afternoon. The fluctuations were a result of changing system variables including: wastewater temperature and organic strength, influent dissolved oxygen concentrations, column gauge pressure, the rate of sand transport between columns, and the concentration of biomass in the reactors. Dissolved oxygen determinations were made two times in every 24-hour period during the week and not at all on weekends.

In general, the oxygen addition rate for the system was primarily a function of the oxygen requirements in column #1 and column #2 where the greatest percent of organic removal was effected. Under many circumstances, oxygen was added only to these two columns and not to subsequent columns in the sequence. Oxygen supplied in a sufficient amount to maintain a dissolved oxygen concentration of 2 to 4 mg/l in the first two columns generally resulted in a dissolved oxygen concentration above 4 mg/l in the remainder of the system due to adsorption of oxygen bubbles not utilized in the first stages. When oxygen gas was added in small amounts (1/10 the rate applied to columns #1 and #2) to subsequent columns downstream of column #2, as in Runs 13, 14 and 15, the average dissolved oxygen concentration increased dramatically in the final half of the system. This phenomenon may be observed in Figure 13 which plots average dissolved oxygen profiles for Runs 7 through 15.

TABLE 10. EBBT MIXED LIQUOR VOLATILE SOLIDS LEVELS - RUN 15

	Mixed Liquor Volatile Solids (mg/l)						
Date	Col. #1	Col. #2	Col. #3	Col. #4	Col. #5	Col. #6	System Avg.
8/14	6,228	360	20,905	12,991	22,145	14,826	10,441
8/16	6,564	3,949	18,478	13,456	23,049	18,965	14,076
8/21	8,457	10,758	12,464	11,214	28,615	18,202	14,951
8/28	6,885	12,386	13,434	18,352	29,870	29,487	18,402
8/30	5,419	17,618	12,984	12,153	16,488	16,262	13,487
9/4	6,219	11,090	14,058	14,513	18,977	19,990	14,141
9/6	5,955	14,045	13,420	14,749	19,493	18,967	14,438
Avg All Dates	6,532	9,965	15,106	13,918	22,662	19,527	14,276

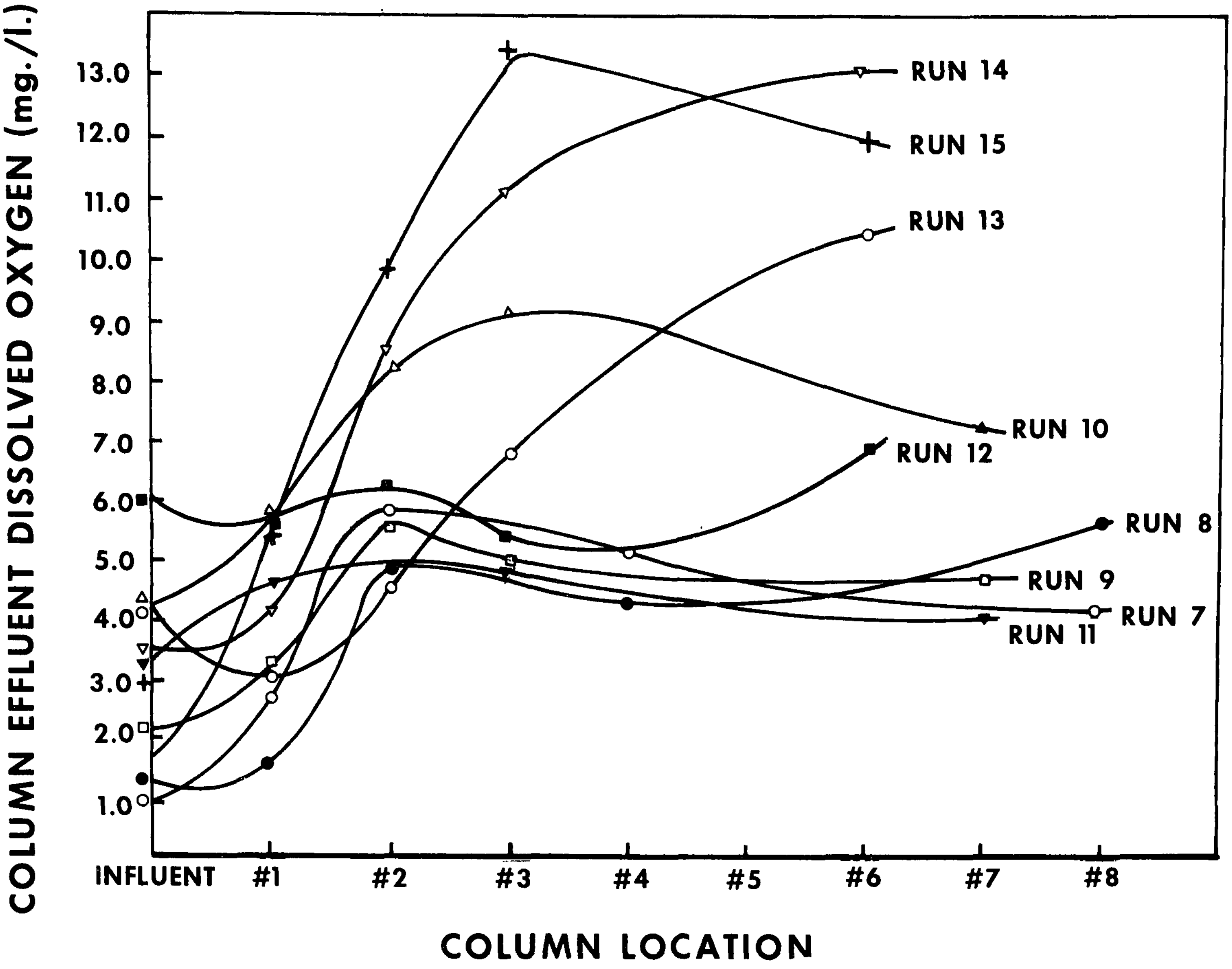

FIGURE 13. SYSTEM AVERAGE DISSOLVED OXYGEN PROFILES FOR RUN 7 THROUGH 15

Oxygen addition rates for all experimental runs are summarized in Table 11. Rates employed ranged from 0.047 to 0.270 kg O_2 added/m^3 (0.388 to 2.246 pounds of O_2 added/1000 gallons) of sewage treated. These represent amounts of oxygen input to the system. This corresponded to an operating range of 0.629 to 1.230 kg O_2 added/kg TCOD removed.

System oxygen utilization efficiency was determined for Run 15. Oxygen input was monitored by measuring weight changes in the feed liquid oxygen cylinders. System off-gases were collected by capping the stilling well in the intermediate clarifier. Gas volume was determined by a wet test meter. A solenoid valve on the meter exhaust would periodically divert a small amount of sample to a mylar collection bag. Samples were analyzed for CO_2, N_2, and O_2 by a local lab within 12 hours of collection. In addition, liquid sampling was expanded to permit a TCOD balance around the system to enable validation of oxygen utilization efficiency on the basis of TCOD destruction.

The test was conducted over a period of five days. Within the first two days, problems developed with the wet test meter. The rate of gas evolution was 2-3 times that anticipated. Repeated tests and recalibration of the instrument failed to locate the difficulty. Consequently, oxygen off-gas had to be determined by difference using the TCOD data. Oxygen utilization efficiency was determined in the following manner.

1) Basic Data

Influent O_2 (lbs) = 0.48 lbs
Effluent O_2 (lbs) from liquid clarifier = 2.26 lbs
Cylinder O_2 applied (lbs) = 67.0 lbs
Influent TCOD (lbs) = 57.57 lbs
Effluent TCOD (lbs) = 11.50 lbs
Waste sludge TCOD (lbs) = 20.05 lbs

2) Calculation

- lbs influent TCOD	57.57
- lbs effluent TCOD	-11.50
- lbs waste sludge TCOD	-20.05
= TCOD destroyed	=26.02 lbs
lbs TCOD destroyed	26.02 lbs
+ Nitrate Nitrogen O_2 demand	
+ lbs effluent dissolved O_2	2.26 lbs
- lbs O_2 supplied	67.48 lbs
= lbs exhaust O_2	39.20 lbs

From this information, the efficiency of oxygen utilization can be seen to be only 38.6 percent. Existing commercially marketed oxygen treatment

TABLE 11. SUMMARY OF OXYGEN ADDITION DATA FOR THE EBBT SYSTEM

Run	System Average Oxygen Addition Rate (cc/min)	Flow (Q) (l/min)*	$\frac{\text{kg } O_2 \text{ added**}}{m^3}$	$\frac{\text{kg } O_2 \text{ Added}}{\text{kg TCOD Removed}}$	$\frac{\text{kg } O_2 \text{ Added}}{\text{kg SCOD Removed}}$
3	1233	31.2	0.047	0.750	0.643
4	750	15.1	0.057	1.110	1.080
5	826	7.6	0.125	0.661	2.970
6	1030	15.1	0.078	0.832	2.270
7	4508	29.9	0.172	-	2.410
8	6245	26.5	0.270	-	3.260
9	1140	26.5	0.049	0.666	2.900
10	1256	18.9	0.076	0.629	2.900
11	1601	18.9	0.097	0.688	2.160
12	1744	18.9	0.105	0.846	2.270
13	2408	18.9	0.146	1.055	1.860
14	3138	18.9	0.190	0.957	2.370
15	3488	18.9	0.210	1.460	5.100

* l/min x 0.265 = gpm

** $\frac{\text{kg } O_2 \text{ added}}{m^3} \times 8.53 = \frac{\text{lbs } O_2 \text{ added}}{1000 \text{ gallons}}$

systems have been able to produce better than 90 percent oxygen utilization by employing off-gas recirculation in staged systems. Clearly, a greater oxygen efficiency would need to be achieved in a full-scale system in order for the process to be competitive.

The poor oxygen utilization efficiency was primarily due to the limitations of the oxygen dissolution method employed in the pilot system. In future testing a more effective oxygen diffuser should be employed. The analyses of the system off-gases in Run 15 indicated an average gas composition of 70.3 percent oxygen, 21.5 percent nitrogen, and 9.3 percent carbon dioxide. The high oxygen content suggests the possibility of also employing off-gas recycle to the beginning of the system or even around each stage.

The most promising approach to improved oxygen utilization efficiency would be dissolution of oxygen gas into the wastewater prior to entry into the column. This would permit large amounts of oxygen to be dissolved without the problem of sand bed instability created by oxygen bubbles in the fluidized bed environment.

EXPANDED BED STABILITY

Through out the EBBT experimental program, considerations of expanded bed stability were involved in nearly all decisions regarding system design, operation, and modification. Treatment performance was directly related to the degree of expanded bed control achieved. The system was considered to be stable when the depth of bed expansion remained relatively constant, and when the rate of daily sand loss was low. It was generally found that reasonably consistent operation was possible at daily loss rates less than 0.4 percent of the total system sand weight expressed in terms of wet sand (20 percent moisture content).

Unacceptable sand loss rates, expecially those greater than 1.0 percent of total system sand/day, were commonly accompanied by severe hydraulic problems and reduced treatment efficiency. Sand was easily transported between columns, but excessive rates of sand movement caused plugging in the connecting piping and flow distribution components. High reactor pressures would develop in these instances, necessitating system shutdown to prevent structural failure of the reactors. Inability to control sand losses resulted in at least 10 column failures and numerous system shutdowns during the three years of experimentation.

In addition to hydraulic difficulties, the loss of media from unstable reactors also reduced treatment efficiency through the attrition of active biological slimes from the system.

Sand losses for each of the thirteen experimental runs are summarized in Table 12. Also shown are the corresponding average values for column rise rates and oxygen addition rate.

Based on total data and observations made during each experimental run, a number of judgements are possible with regard to EBBT bed stability. First

TABLE 12. SUMMARY OF WET SAND LOSS FROM THE EBBT SYSTEM

Run	Column Rise Rate $1/min/m^2$	Average Oxygen Addition Rate (S.T.P.) cc/min	Average Oxygen Addition Rate (S.T.P.) kg/m^3	Average Wet Sand Loss kg/day	Average Wet Sand Loss % of Bed Weight
3	816.0	1233	0.047	1.86	0.63
4	652.8	750	0.057	0.86	0.29
5	163.2	826	0.125	0.39	0.13
6	326.4	1030	0.078	1.76	0.60
7	664.6	4508	0.172	4.82	0.50
8	571.2	6245	0.270	4.15	0.44
9	571.2	1140	0.049	17.3	1.7
10	571.2	1256	0.076	17.7	1.8
11	571.2	1601	0.097	3.4	0.36
12	408.0	1744	0.105	4.1	0.60
13	408.0	2408	0.146	7.7	1.13
14	408.0	3138	0.190	27.5	4.03
15	408.0	3438	0.210	3.0	0.31

of all, the rate of sand loss was more sensitive to the amount of attached biological slimes and the volume of oxygen gas applied to the system than it was to changes in column rise rate. The principal importance of the column rise rate over the 163.2 to 816 $1/min/m^2$ (4 to 20 gpm/ft^2) range examined was the determination of the degree of bed expansion.

Rise rate was related to the loss rate only in the sense that it aggravated the effects of excess biological growth on the sand particles and the "bubble effect". High rise rates were not the causative factor in sand loss, as long as sufficient free board was available.

In the case of EBBT, the bubble ring devices placed at the reactor effluent proved effective protection against media losses. Treatment efficiency and allowable reactor biological mass concentration were therefore not limited by oxygen dissolution considerations.

The question of what constitutes "excess" biological growth on the media particles is a more fundamental one. The EBBT experimentation was not extensive enough to provide the data necessary to establish an optimum ratio of bacterial mass to media mass. Throughout the research the principal goal with regard to effective mixed liquor biological mass was to maintain the highest concentration possible, allowing natural sloughing to determine the limit of permissible growth. Based on the hydraulic problems which were encountered throughout the study as a consequence of this approach it is apparent that maximum mixed liquor biological growth is not necessarily consistent with maximum treatment efficiency.

Clearly, some positive means of controlling the amount of growth per sand particle is necessary. Growth could be controlled through an external means of forced sloughing, such as a small "blow-down" tank into which a portion of the expanded bed would be discharged periodically from each reactor. If the shearing forces exerted during the transport were insufficient a mixer could be used to assist in dislodging the necessary amount of bacterial growth. After a very short settling period the sludge mass could be decanted to waste and the sand media returned to the reactor.

Rather than controlling sand loss by limiting the amount of bacterial growth per media particle it may be possible to solve the problem merely by using a denser media material such as garnet. In the same range of rise rates employed with sand media, the denser particles would have a decreased rate of expansion (i.e., greater resulting freeboard depth) and possibly a reduced sensitivity to varying degrees of biological growth on the particles. These attributes might permit either the use of higher reactor rise rates, increased growth per particle, or the use of more media (number of particles) per reactor than was possible with sand of a similar size distribution. Any of these possible benefits would have to be weighed against both the increased cost of the media and the greater resulting head losses through the fluidized bed.

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16. ABSTRACT

The performance of a three-phase fluidized bed biological contacting system for secondary treatment of settled wastewater was investigated in a 37.9 l/min. pilot plant. The system consisted of a series of two to eight reactors partially filled with fine sand. Wastewater was passed upwards through the reactors, fluidizing the sand, while providing a large surface area upon which bacteria could grow. Aerobic conditions were maintained by supplying high-purity oxygen gas to the influent of each reactor stage.

The process achieved an average TCOD removal efficiency of 75 percent and an effluent TCOD of 48.8 mg/l (13 mg/l $TBOD_5$) at an empty bed retention time of 44 minutes and a TCOD loading rate of 6.4 $kg/m^3/day$. Secondary effluent guideline quality was possible at a retention time as short as 25 minutes. System MLVSS concentrations ranged from 14,000 to 16,000 mg/l, with net waste solids production ranging from 0.26 to 0.57 kg VSS/kg TCOD removed at solids retention times of 8.7 days and 5.2 days respectfully.

System performance was found to be directly proportional to the ability to control excess biological growth on the sand and prevent sand particles from washing out of the system.

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