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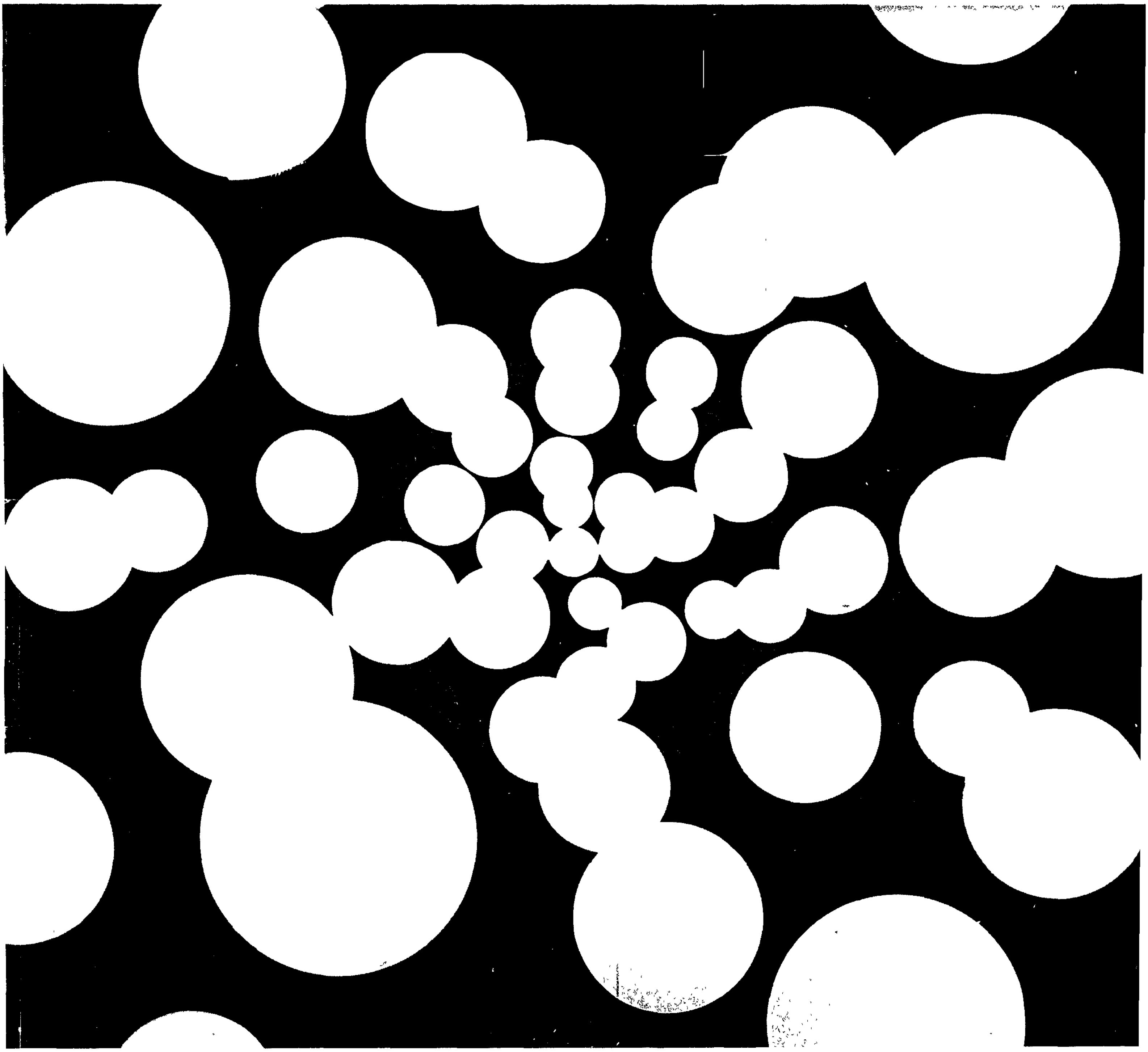
Oxygen Activated Sludge Wastewater Treatment Systems

Design Criteria and Operating Experience

EPA Technology Transfer Seminar Publication



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OXYGEN ACTIVATED—SLUDGE WASTEWATER TREATMENT SYSTEMS

Design Criteria and Operating Experience

ENVIRONMENTAL PROTECTION AGENCY • Technology Transfer

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NOTICE

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INTRODUCTION

The recent and accelerating emphasis on protection of the environment has necessitated the rapid development of improved technology to aid in pollution control. The use of oxygen in place of air in the activated-sludge process is one recent advancement in this basic process. The potential of this development, in terms of higher quality treatment from existing plants and construction of new facilities at reduced cost, has resulted in extremely rapid acceptance by municipalities and industry.

The primary distinguishing feature of the Unox system (see fig. 1) is that high-purity oxygen is the source of oxygen for the micro-organisms in the aeration basin, as opposed to air as the source in conventional activated-sludge systems. The concept of using oxygen in this manner is not new; many investigators have performed work since the early 1940's to demonstrate the feasibility of a high-purity-oxygen activated-sludge process. The major deterrent to oxygen use in the processes envisaged by these early investigators was economics, with objections centering mainly around the cost of oxygen production and the problem of sufficient consumption of the high-purity oxygen to achieve a cost-effective system. This lack of an economically attractive system notwithstanding, enough experimental work was performed by early workers to indicate many desirable features for systems using a higher purity source of oxygen than for air-activated-sludge processes.

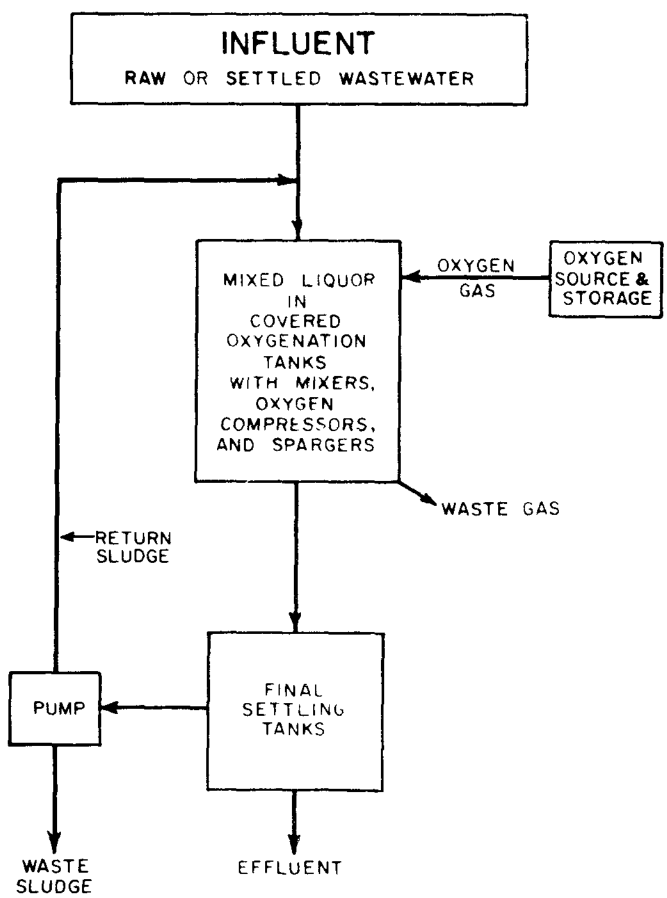

Figure 1 Unox process

The Linde Division of Union Carbide Corporation began active experimentation with the use of pure oxygen in the activated-sludge process during the mid-1960's. In 1969, bench-scale and pilot-plant investigation culminated in a full-scale demonstration of the Unox system at Batavia, N.Y., under Federal Government sponsorship.[1,2]

At the conclusion of the Batavia demonstration, Union Carbide recognized the necessity of demonstrating the widespread applicability and highly desirable performance characteristics of the Unox system on a variety of wastewaters. Accordingly, 10 demonstration-size pilot plants were constructed and have been operated at approximately 30 locations in the United States, covering a broad range of wastewater characteristics.

The economic use of oxygen in the activated-sludge process requires the availability of relatively inexpensive, high-purity oxygen gas in tonnage quantities. This capability had been developed in the 1950's in the form of efficient large tonnage cryogenic air-separation plants to produce high-purity oxygen gas. A substantial distribution network also exists in the United States for bulk quantities of liquid oxygen. Thus oxygen use in the activated-sludge process was feasible from an oxygen-supply standpoint, even before the process development to use oxygen supply effectively over a broader range, through the use of pressure-swing adsorption to produce reliable high-purity oxygen in small quantities.

Chapter I

UNOX-SYSTEM DESCRIPTION

The Unox system uses a covered and staged oxygenation basin (fig. I-1) for contact of oxygen gas and mixed liquor. High-purity oxygen (90-100 percent volume) enters the first stage of the system and flows cocurrently with the wastewater being treated through the oxygenation basin. Pressure under the tank covers is essentially atmospheric, being from 2 to 4 inches water column, sufficient to maintain control and prevent backmixing from stage to stage. This procedure allows for efficient oxygen use at low power requirements. Effluent mixed liquor is separated in conventional gravity clarifiers, and the thickened sludge is recycled to the first stage for contact with influent wastewater.

Mass transfer and mixing within each stage is accomplished either with surface aerators or with a submerged-turbine rotating-sparge system. In the first case, mass transfer occurs in the gas space; in the latter, gas is sparged into the mixed liquor where mass transfer occurs from the gas bubbles to the bulk liquid. In both cases, the mass-transfer process is enhanced by the high oxygen-partial pressure maintained under the tank covers in each stage. As a consequence of the increased oxygen-partial pressure, it is feasible to maintain higher dissolved oxygen (DO) levels in the mixed liquor relative to those achievable with air, and to achieve oxygen dissolution with substantially lower energy inputs to the mixed liquor than would be required with air. Thus, the effective transfer efficiency of a mass-transfer device in oxygen service will be greater than its standard transfer efficiency, whereas the opposite is true with the same device operating in air.

The selection of the number of stages, the number of parallel biological reactors, and the type of mass-transfer device to employ are variables that depend on waste characteristics, plant size, land availability, treatment requirements, and other similar considerations. In practice, the consultant will have essential input to the oxygen-system design or to establishing the actual design.

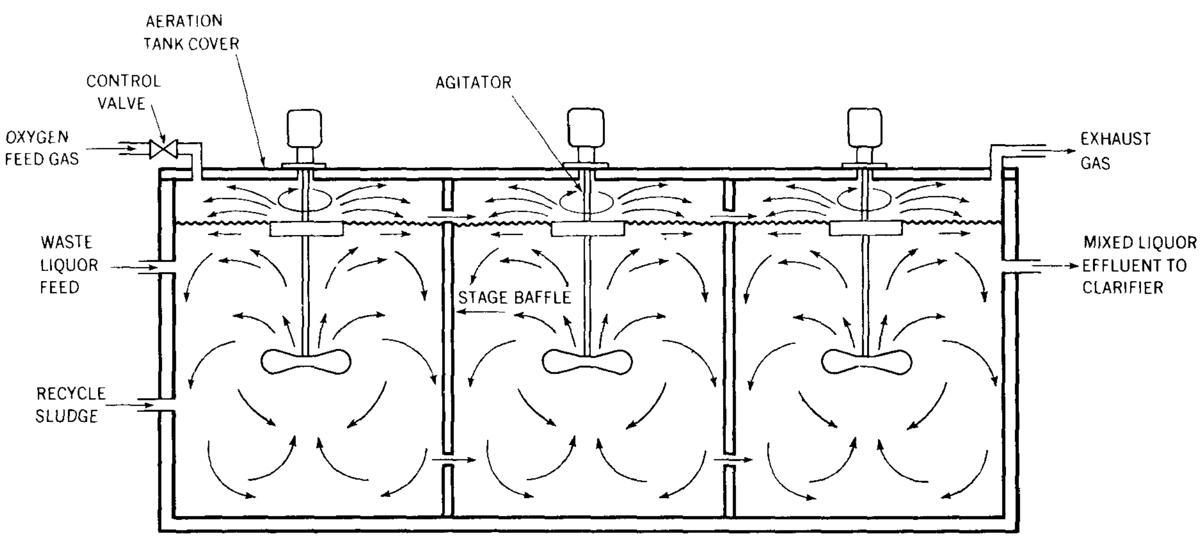

Figure I-1. Schematic diagram of Unox system with surface aerator, showing three stages.

The Unox system has other important benefits. The maintenance of high DO levels with low energy input to the mixed liquor contributes to a highly aerobic biological mass that flocculates well. These factors are responsible for enhanced settling characteristics relative to air systems, so that with conventional clarification designs a much higher level of mixed-liquor suspended solids (MLSS) (4,000-8,000 mg/l) can be carried in the biological reactor than is normally achievable with air-activated sludge. This factor is used in design to reduce the required reactor detention time while still maintaining a design food-to-biomass (F/M) level very similar to common practice in air systems. High DO levels are also an important factor contributing to lower excess solids production than is commonly achieved with air-activated-sludge systems at comparable biomass loadings.

Since the oxygen gas fed to the system is devoid of nearly all nitrogen, and since approximately 90 percent of the oxygen gas normally is used, the total gas venting from the system is only about 1 percent of the gas vented from an air-activated-sludge system. Since the reactors are covered, this gas is vented at one point; thus effective odor control is achieved and the biological aerosol problem typical of air systems is eliminated.

The process control of the Unox system is very simple. Since the tank is covered, the biological reactor acts essentially as a respirometer. Thus, pressure control can be used to control the oxygen feed rate. A simple pressure sensor is installed in the first-stage tank cover; this device detects changes in gas pressure resulting from a decrease or increase in oxygen uptake as flow or strength changes. A signal is relayed to a flow-control valve on the inlet oxygen line, which adjusts oxygen flow to maintain the desired gas-pressure setpoint under the first-stage cover. Thus, if flow or 5-day biochemical oxygen demand (BOD_5) increases, resulting in a lowering of gas pressure in the first-stage gas space, the control valve will open causing more oxygen to flow to the system. This simple control circuit provides real-time response to the BOD_5 demands placed on the system. It is also possible to automate the oxygen-production unit to respond to these changes in demand, thereby causing the system to use only the appropriate power for oxygen generation commensurate with the BOD_5 load placed on it.

Chapter II

OPERATING DATA AND EXPERIENCE

OPERATING EXPERIENCE AND RESULTS FROM SPECIFIC PROGRAMS

The design of Unox systems today is based upon published technology for design of conventional activated-sludge processes and upon a very large amount of data accumulated in pilot-plant demonstrations and Union Carbide-funded development programs. Operating experience with oxygen-activated-sludge systems commenced with pilot programs before the Government-funded Batavia demonstration work. Since the conclusion of the initial work at Batavia, a comprehensive pilot-plant program has been maintained using a total of 10 pilot plants. These pilot plants have been and are being used throughout the United States (and in certain foreign countries) to demonstrate the Unox-system capabilities to consultants, municipalities, and industries, and to obtain design data for the specific waste stream being studied. As of this time, programs have been completed in a total of 30 locations encompassing nearly 18 years of operating experience (table II-1). Programs are currently underway in eight additional locations (table II-2).

A typical pilot-plant program will involve setting up a pilot plant at the customer's site and assisting the customer's personnel in the operation of the plant. All analytical work normally is performed by the customer at his plant laboratory. Most pilot-plant programs have extended over a 4-6-month period, although some have been conducted for as long as 1 year. Each program normally includes one phase of operation at steady-state flow at approximately the biomass loading anticipated for a system design. Following this phase, the plant is operated on a diurnal flow cycle to simulate the anticipated hydraulic pattern expected at the site. Subsequent operational phases will include sustained operation at high biomass loadings or high hydraulic flows to simulate more severe conditions than normally expected in the actual design. During each operating phase a full complement of data is taken in the plant by regularly sampling influent, effluent, mixed liquor, recycle, and sludge-waste streams and by regularly reading all plant-operating indicators 24 hours per day, 7 days per week.

Two types of pilot plants are used in these applications. The majority of the plants are mounted within 40-foot warehouse van trailers, so that they can be easily transported around the country and simply placed into operation. The others are somewhat smaller portable plants that can be relocated quite easily but require a building for weather protection, as well as slightly more extensive installation service than is required for the mobile plants. The mobile plant has a nominal capacity of up to 43,000 gpd, whereas the portables operate at up to 7,500 gpd.

The mobile unit is a completely enclosed, secondary wastewater-treatment system with an external secondary clarification unit. All tankage, instrumentation and controls, pumps, and a small laboratory are contained within the 40-foot warehouse van trailer. A schematic diagram of a three-stage unit is presented in figure II-1.

As indicated, the oxygenation tankage in the mobile pilot facility is divided into four sections, or stages, by means of baffles, and is covered to provide a gastight enclosure. The liquid and gas phases flow concurrently through the system. Raw wastewater, recycle-sludge, and oxygen gas are introduced into the first stage. The pilot unit has the flexibility to be operated as a two-, three-, or

Table II-1.—*Completed pilot-plant operations*

Location	Duration, months	Wastewater type	Component	Consultant
Northeast	6	Raw degritted	Domestic	
Batavia, N.Y	6	Raw degritted	Dairy-product processing, domestic	
Mid-Atlantic	5	Primary effluent	50% industrial-chemical producing, domestic	
Midwest	3	Primary effluent Intermediate trickling-filter effluent, intermediate clarifier effluent	Grain processing, meat-packing, domestic	
Mid-Atlantic	6	Primary effluent	Pulp and paper mill waste, Kraft process waste	
Cincinnati, Ohio	8	Primary effluent	40% industrial, domestic	Malcolm Pirnie
Midwest	4	Primary effluent	Various industries to 60% Q, domestic	
Grand Island, N Y	3	Primary effluent	Domestic	
Mid-Atlantic	4	Primary effluent	Chrome plating, dye producing, exotic alloy manufacturers, domestic	
Southeast	3	Primary effluent	Brewery waste	
Louisville, Ky	9	Primary effluent, primary effluent with industrial	Distilleries, dairy product, slaughterhouses, chemical manufacturers, domestic	Consoer & Townsend
Miami, Fla	3	Raw degritted	Domestic	Miami
Middlesex, N J	11	Raw degritted	Pulp and paper manufacturers, food processors, chemical manufacturers, plastics, domestic	Metcalf & Eddy
Southeast	2	Raw degritted	Textile, poultry process, domestic	
New Orleans, La	6	Raw degritted	Breweries, seafood processing, poultry processing, domestic	W. S Nelson
Northeast	8	Raw degritted	Pulp and paper manufacturers, plastics producers, domestic	
West	5	Primary effluent	Canning-process water, 50% industrial, domestic	
Northeast	9	Primary effluent	30% organic dye producing, domestic	
Northeast	7	Primary effluent	60% combined industrial, domestic	
Northeast	9	Primary effluent	60% industrial, 40% domestic	
Northeast	3	Primary effluent	Domestic, brewery	
Northeast	3	Primary effluent	Domestic, industrial	
West	3	Primary effluent	Domestic, canning waste	
Midwest	6	Primary effluent	Industrial-chemical, dairy, brewery, food, domestic	
Northwest	5	Primary effluent	Domestic, canning waste	
Charleston, W. Va	3	Primary effluent	Petrochemical, domestic	Union Carbide
Taft, La	9	Lagoon effluent	Petrochemical	Union Carbide
Southeast	6	Primary effluent	Domestic, brewery, nitrification	
Northeast	4	Raw degritted	Chemical producers, coke producers, refineries, domestic	
Midwest	4	Primary effluent	Domestic	

Table II-2.—*Current pilot-plant operations*

Location	Wastewater type	Component
Blue Plains, Washington, D.C.	Primary effluent	Domestic
Southwest	Holding pond effluent	Petrochemical
Midwest	Raw degritted	30% combined industrial, 70% municipal
West	Primary effluent	Combined industrial, municipal
Northeast	Primary effluent	Domestic
Southeast	Stabilization pond effluent	Organic, chemical waste
Northeast	Secondary effluent	Domestic, nitrification
Northeast		Coke oven waste
Northeast	Raw degritted	Combined municipal, industrial
West		Pulp and paper mill process water

four-stage system. The number of stages employed may vary, depending on the specific application. Each of the stages is a completely mixed unit with the overall four-stage system approximating a plug-flow-type reactor. The wastewater and the biomass return are mixed upon entering the first stage. The pilot-plant wastewater-feed and sludge-recycle pumps are calibrated, variable-speed units. Their operating speeds are used to monitor the influent and recycle flows.

During operation, high-purity oxygen gas is fed into the first-stage gas space; the gas pressure is maintained at about 1 inch of water above the atmospheric. The oxygen-enriched gas flows through interstage gas passages and is vented to the atmosphere through a volumetric flowmeter. The slight pressure drop between successive stages is sufficient to prevent backmixing of the oxygen-enriched gas. The staged gas-phase oxygen compositions are measured periodically with a paramagnetic oxygen analyzer. As the oxygen-enriched atmosphere passes through the system, small diaphragm compressors in each stage pump the gas down the hollow mixer shaft and through the rotating sparger at a rate sufficient to maintain a DO concentration of approximately 7 mg/l. The oxygen-gas feed is measured volumetrically and controlled automatically by the gas-phase pressure in the first stage.

Effluent from the biological reactor flows to a center feed clarifier, which contains a peripheral effluent weir and a plow-type scraper with a center takeoff for settled solids.

In addition to the monitoring of gas and the liquid flows by appropriate metering and recording equipment, several basic parameters are measured to determine the system performance. Composite samples of the bioreactor influent, the clarifier effluent, and the sludge recycle are formed from grab samples taken frequently. Wastewater-flow and gas-flow measurements are taken to correspond to each of the composites formed.

Grab samples of the mixed liquor from stages 1 and 4 are taken three times daily for solids and settling tests. Solids are wasted from the clarifier semicontinuously in an attempt to approximate a full-scale system. The volumes wasted are measured, and grab samples of the solids recycle are taken for solids analysis. Grab samples are also taken from stages 2 and 3 once each day for solids analysis. Virtually all of the analytical procedures are carried out as prescribed in the 13th edition of *Standard Methods.*[3]

The results from many of the pilot-plant operations are included in tables II-3 to II-7.

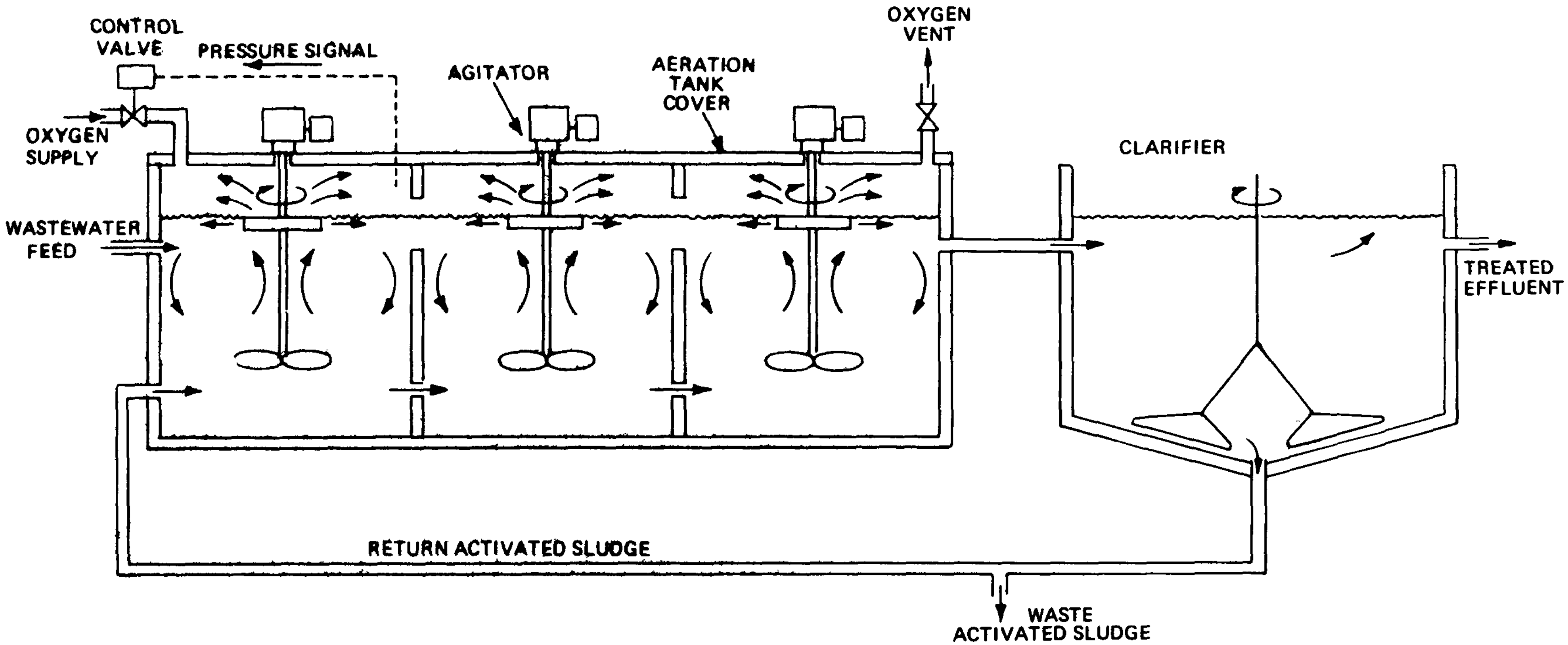

Figure II-1. Schematic diagram, three-stage Unox system.

Table II-3.—*Unox-system pilot-test data, performance summary for locations A and B*

Component	Unit	Location A		Location B	
		Phase I	Phase II	Phase I	Phase II
Retention time	Hours	1.8	1.6 (0.89-2.1)	1 8	2.0
Recycle ratio	Percent	28	28	37	0 30
Sewage temperature	°F	57	66	84	80
MLSS	mg/l	6,100	4,000	5,060	7,010
VSS/TSS		0 62	0.74	0 76	0.77
Organic loading	Pounds BOD per 1,000 ft^3/day	165	190	198	171
Biomass loading	Pounds BOD per pound MLVSS/day	0.66	1.02	0.83	0.50
Influent characteristics:					
COD	mg/l	375	365	471	467
BOD_5	mg/l	185	200	238	227
Suspended solids	mg/l	180	135	83	76
Effluent characteristics:					
COD	mg/l	88	72	106	81
BOD_5	mg/l	21	17	10	8
Suspended solids	mg/l	20	16	27	15
Removals:					
COD	Percent	77	80	76	82
BOD_5	Percent	89	92	95	96
Suspended solids	Percent	89	88	64	80
Clarifier overflow rate	gal/ft^2/day	660	710 (520-1,300)	650	582
Clarifier mass loading	Pounds SS/ft^2/day	45	29 (23-75)	27.3	44.5
Clarifier underflow concentration	Percent	2.6	1.7	1.9	3.13
Sludge-volume index	-	40	61	55	42
Pounds VSS per pound BOD_5 removed:					
Accumulation	-	0.718	0.581	0.42	0.367
For disposal	-	0.64	0.515	0.33	0.272
Pounds O_2 per pound BOD_5 removed	-	0.89	0.94	1.32	1.35
Pounds O_2 per pound COD removed	-	0.689	0.602	0.72	0.77
COD/BOD ratio	-	2.08	1.83	2.42	2.06
Solids retention time	-	2.11	1.69	2.87	5.45

CORRELATION OF RESULTS FOR DESIGN

From the results of the large number of programs already completed and from the design information available on conventional activated sludge, it is possible to develop some useful relationships of value in design of a Unox system for a specific waste stream. The most important of these relationships include substrate removal, oxygen requirements, excess solids production, and solids-liquid separation characteristics.

Substrate Removal

The design of Unox systems is closely keyed to the use of biomass loading as a parameter for design. Conventional air-activated-sludge processes are typically designed for biomass loadings of 0.3 to 0.5, based on volatile solids in most cases. This range of operation represents an equitable balance between retention time and sludge accumulation and provides for a stable operating mode. Unox systems generally are designed on the same basis, except that the range of biomass loadings is somewhat higher. Most designs are made at average biomass loadings of 0.5-0.8. When oxygen is not limiting, it is possible to design at this increased level due to the enhanced ability to transfer

Table II-4 –*Unox-system pilot-test data, performance summary for locations C and D*

Component	Unit	Location C		Location D, phase I
		Phase I	Phase II	
Retention time	Hours	1.8	1 07	2 2 (1 4-3.2)
Recycle ratio	Percent	30	22	31
Sewage temperature	°F	75	72	67
MLSS	mg/l	5,800	4,900	6,200
VSS/TSS		0 8	0 79	0.77
Organic loading	Pounds BOD per 1,000 ft^3/day	147	208	143
Biomass loading	Pounds BOD per pound MLVSS/day	0.51	0.85	0 48
Influent characteristics				
COD	mg/l	460	392	454
BOD_5	mg/l	177	145	209
Suspended solids	mg/l	143	120	126
Effluent characteristics				
COD	mg/l	124	181	90
BOD_5	mg/l	14	19	11
Suspended solids	mg/l	36	31	30
Removals				
COD	Percent	73	54	80
BOD_5	Percent	91	87	95
Suspended solids	Percent	75	74	76
Clarifier overflow rate	gal/ft^2/day	640	1,085	529 (350-800)
Clarifier mass loading	Pounds SS/ft^2/day	40	53	32 6
Clarifier underflow concentration	Percent	2.3	3 0	2 3
Sludge-volume index	-	47	41	56
Pounds VSS per pound BOD_5 removed				
Accumulation	-	0 52	0.83	0 64
For disposal	-	0.33	0 62	0 50
Pounds O_2 per pound BOD_5 removed	-	1.32	1 23	1 06
Pounds O_2 per pound COD removed	-	0 64	0 73	0 58
COD/BOD ratio	-	2 6	2 7	2 17
Solids retention time	-	3 75	1 42	3 36

oxygen to support metabolism without destructively high energy inputs to the mixed liquor. Figure II-2 presents the data correlating F/M removed against phase-average biomass loading for pilot-plant results in tables II-3 to II-7. The slope of the line represents the percentage BOD_5 removal.

The range of secondary-system removals varied from 87 to 97 percent for all programs presented as a group for phase-average biomass loadings as high as 1.4. It is evident that the process can be sustained reliably and can achieve high substrate removal at the design-average biomass-loading range of 0.5-0.8. Figure II-2 also shows that the process will perform well during diurnal or peak organic-load periods (represented by phase-average data, as high as 1.4) when biomass loadings will exceed the design range for some period of time, provided that oxygen is not limiting. This factor is important in maintaining consistently high-quality treatment.

Figure II-3 is a comparable presentation of the data based on the organic-loading parameter pounds BOD_5 per 1,000 cubic feet oxygenation tankage per day.

Oxygen Requirements

The total oxygen requirements in the activated-sludge system are related to the oxygen required for synthesis and to that associated with endogenous respiration. Since the Unox system is a closed

Table II-5.—*Unox-system pilot-test data, performance summary for locations E and F*

Component	Unit	Location E		Location F	
		Phase I	Phase II	Phase I	Phase II
Retention time	Hours	1.8	1.8	1.7 (1.1-2.8)	1.3 (1.2-1.5)
Recycle ratio	Percent	25	26	27	26
Sewage temperature	°F	70	78	87	87
MLSS	mg/l	5,600	7,350	6,200	5,950
VSS/TSS		0 66	0.74	0.75	0.83
Organic loading	Pounds BOD per 1,000 ft^3/day	181	193	162	196
Biomass loading	Pounds BOD per pound MLVSS/day	0.76	0.56	0 55	0.64
Influent characteristics					
COD	mg/l	308	377	380	398
BOD_5	mg/l	210	229	184	170
Suspended solids	mg/l	191	236	183	172
Effluent characteristics					
COD	mg/l	64	66	67	63
BOD_5	mg/l	12	12	6	5
Suspended solids	mg/l	18	28	17	13
Removals					
COD	Percent	79	82	82	84
BOD_5	Percent	94	95	97	97
Suspended solids	Percent	98	88	91	92
Clarifier overflow rate	gal/ft^2/day	650	650	730 (420-1,060)	890 (780-1,000)
Clarifier mass loading	Pounds SS/ft^2/day	37	50	41	52
Clarifier underflow concentration	Percent	2.5	3.2	2.7	2.3
Sludge-volume index	-	79	48	55	55
Pounds VSS per pound BOD_5 removed.					
Accumulation	-	0.53	0.38	0.31	0 36
For disposal	-	0 45	0 27		
Pounds O_2 per pound BOD_5 removed	-	0.81	1.03	1.22	1.07
Pounds O_2 per pound COD removed	-	0 65	0 72	0 70	0 53
COD/BOD ratio	-	1.47	1 64	2 06	2 32
Solids retention time	-	2.5	4.7	5.85	4 25

system, and oxygen-containing gas is monitored for both flow and concentration, it is apparent that the oxygen consumed per unit of BOD_5 removed may be determined readily. Figure II-4 presents a correlation of oxygen consumption per unit BOD_5 removal as a function of biomass loading for several plants and types of waste. At high food-to-micro-organism ratios, oxygen requirement per unit BOD_5 removal is governed mainly by oxygen required for cell synthesis, since the degree of endogenous respiration is relatively low as is indicated by higher excess sludge production at high food-to-micro-organism ratios. At low food-to-micro-organism ratios the degree of auto-oxidation increases, the oxygen requirement increases, and the quantity of excess sludge produced decreases.

A second, and most important, factor for determining the oxygen requirement is the COD/BOD_5 (chemical oxygen demand to BOD_5) ratio. Increasing the COD/BOD_5 ratio results in increasing the oxygen consumption per unit removal, which is opposite to the effect of increasing F/M.

The COD test measures the total oxidation potential of the wastewater substrate. This test includes biodegradable materials as well as nonbiodegradable or refractory substances. The BOD_5 test measures some fraction of the biodegradability relative to the COD. In an activated-sludge process, the amount of substrate removed biologically generally will exceed the indicated BOD_5. This incremental removal in excess of the measured influent BOD_5 represents biodegradable COD not entirely detected in the standard BOD_5 test. Thus, the COD/BOD_5 ratio is indicative of the relative (biological) toughness and total organic strength of the waste.

Table II-6 —*Unox-system pilot-test data, performance summary for locations G and H*

Component	Unit	Location G, Phase I	Location H	
			Phase I	Phase II
Retention time	Hours	1.8	1.8	2 2
Recycle ratio	Percent	36	33	33
Sewage temperature	°F	70	96	94
MLSS	mg/l	4,190	5,300	6,600
VSS/TSS		0.79	0.88	0.9
Organic loading	Pounds BOD per 1,000 ft^3/day	145	230	200
Biomass loading	Pounds BOD per pound MLVSS/day	0.72	0.89	0.54
Influent characteristics.				
COD	mg/l	321	893	888
BOD_5	mg/l	177	274	294
Suspended solids	mg/l	90	84	79
Effluent characteristics				
COD	mg/l	60	425	357
BOD_5	mg/l	13	22	27
Suspended solids	mg/l	25	49	46
Removals:				
COD	Percent	84	52	60
BOD_5	Percent	93	92	90
Suspended solids	Percent	71	42	40
Clarifier overflow rate	gal/ft^2/day	650	650	520
Clarifier mass loading	Pounds SS/ft^2/day	30.1	33	34
Clarifier underflow concentration	Percent	1.47	2.0	2.7
Sludge-volume index	-	64	90	130
Pounds VSS per pound BOD_5 removed				
Accumulation	-	0.60	0.36	0.41
For disposal	-	0.49	0.2	0.26
Pounds O_2 per pound BOD_5 removed	-	0.93	1.28	1.46
Pounds O_2 per pound COD removed	-	0.71	0.68	0.73
COD/BOD ratio	-	1.81	3.35	3.0
Solids retention time	-	2.33	3.52	4.5

Within any activated-sludge system, the micro-organisms attack all of the organic substrate available to them—not only BOD_5, but also BOD_{20}, BOD_{100}, and so forth, almost all of which are included in the COD measure. Because BOD_5 is relatively easy to degrade, it is almost completely assimilated, whereas a smaller portion of the BOD_{20} (hard to degrade) is assimilated, and most of the BOD_{100} (very hard to degrade) will pass through the system unaffected.

As the COD/BOD_5 ratio in the influent increases, the data from Unox pilot plants indicate that a higher quantity (poundage) of the COD will be biologically removed, although such removal is not indicated in the BOD_5 test. Consequently, more oxygen is required per unit BOD_5 removed; however, for COD removal oxygen consumption will remain relatively stable over the design range of food-to-micro-organism ratios employed.

Figure II-4 represents the band of data that will result from oxygen consumption per unit BOD_5 removal when both F/M and COD/BOD_5 ratios are investigated.

Excess Sludge Production

The extent of net or excess solids production is a function of the degree of endogenous respiration occurring in the oxygenation system. The degree of endogenous respiration is governed by the food-to-micro-organism ratio. Since the Unox system employs a multistage gas-liquid-contacting

Table II-7.—*Unox-system pilot-test data, performance summary for locations I and J*

Component	Unit	Location I		Location J	
		Phase I	Phase II[1]	Phase I[1]	Phase II
Retention time	Hours	1.8	1.85	1.5	0.75
Recycle ratio	Percent	29	42	25	25
Sewage temperature	°F	65	64	73	64
MLSS	mg/l	4,700	4,200	4,000	4,200
VSS/TSS		0.84	0.85	0.72	0.76
Organic loading	Pounds BOD per 1,000 ft^3/day	350	280	117	286
Biomass loading	Pounds BOD per pound MLVSS/day	1.4	1.2	0 67	1.44
Influent characteristics:					
COD	mg/l	826	825	260	400
BOD_5	mg/l	415	331	133	143
Suspended solids	mg/l	180	386	160	136
Effluent characteristics:					
COD	mg/l	99	132	57	95
BOD_5	mg/l	12	23	11	15
Suspended solids	mg/l	18	42	19	32
Removals:					
COD	Percent	88	84	78	76
BOD_5	Percent	97	93	92	89
Suspended solids	Percent	90	89	87	77
Clarifier overflow rate	gal/ft^2/day	520	530	588	782
Clarifier mass loading	Pounds SS/ft^2/day	31.0	26.0	24.1	34.2
Clarifier underflow concentration	Percent	1.5	1.3	1.9	1.8
Sludge-volume index	-	82	85	106	94
Pounds VSS per pound BOD_5 removed:					
Accumulation	-	0.67	1.23	0.61	1.10
For disposal	-	0.64	1.08	0.46	0.86
Pounds O_2 per pound BOD_5 removed	-	0.85	0.90	[2]1.60	0.98
Pounds O_2 per pound COD removed	-	0.42	0.36	0.86	0.40
COD/BOD ratio	-	2.00	2.50	1.95	2.80
Solids retention time	-	1.06	0.68	2.44	0.63

[1]Unclarified trickling-filter effluent.
[2]Partial nitrification occurring.

approach, with all streams entering the first stage, the food-to-micro-organism ratio decreases rapidly from stage to stage. Therefore, a high degree of stabilization occurs in the latter stages, resulting in decreased sludge production. It has also been determined that a high-DO environment will result in a lower sludge yield owing to the highly aerobic character of the biological floc. In essence, this means that all floc particles are in a working mode and, when placed in a food-limiting situation, will therefore undergo a higher degree of endogenous respiration or auto-oxidation than will floc in a low-DO environment. The measurement of sludge production in any biological process is difficult and requires careful control of wasting schedules and system-sludge-inventory levels, as well as careful analytical monitoring of the system. If care is not taken, misleading results easily can be obtained. In Unox pilot-plant programs, extensive solids-production data are taken regularly.

Figure II-5 represents a relationship between excess sludge production and solids retention time, which has been developed from some of the Unox programs. As indicated, sludge production increases as the solids retention time (SRT) decreases (food-to-biomass ratio increases). Higher biomass loadings result in an increase in cell synthesis and a decrease in endogenous respiration. The phase-average data points presented have been corrected for changes in system inventory due to solids accumulation or losses that may be attributed to sludge production.

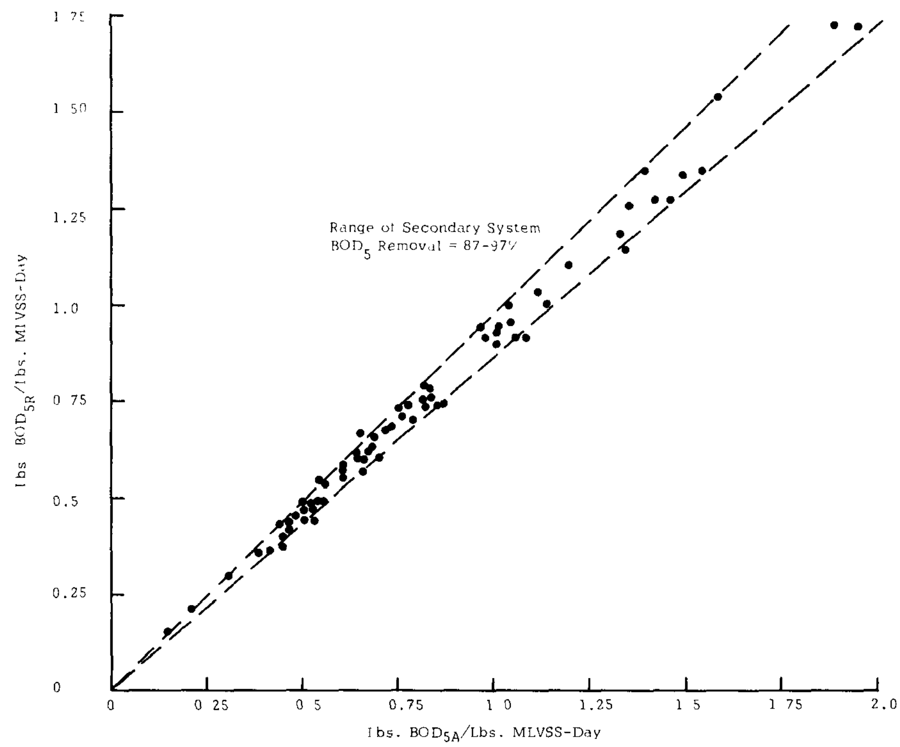

Figure II-2. Unox system, organic removal as a function of biomass loading.

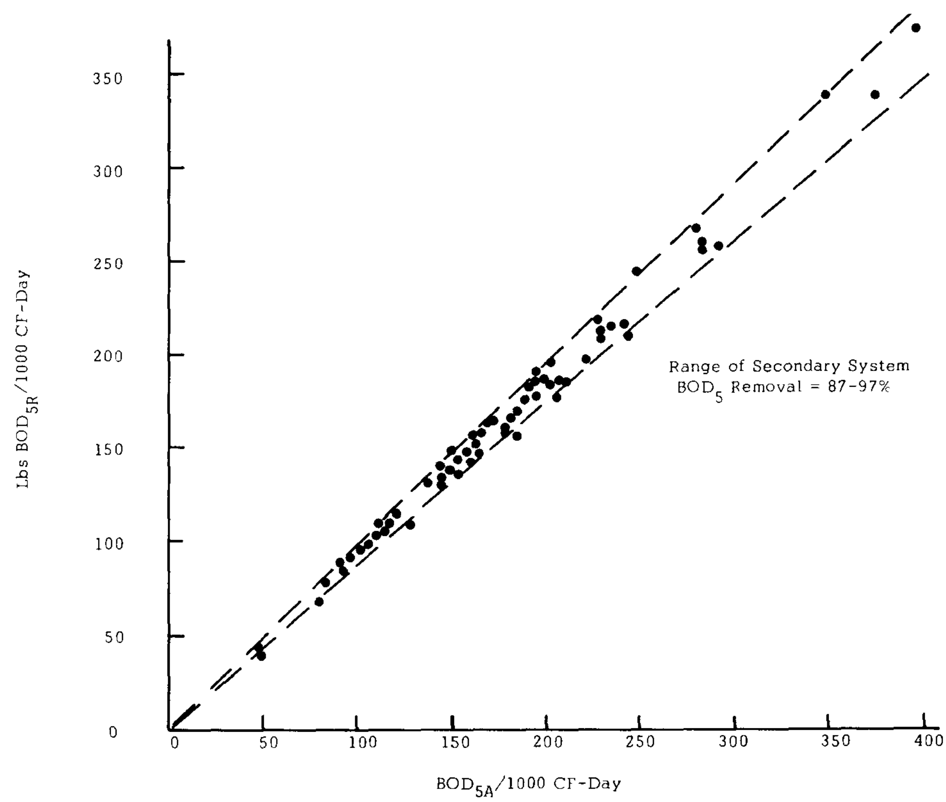

Figure II-3. Unox system, organic removal as a function of organic loading.

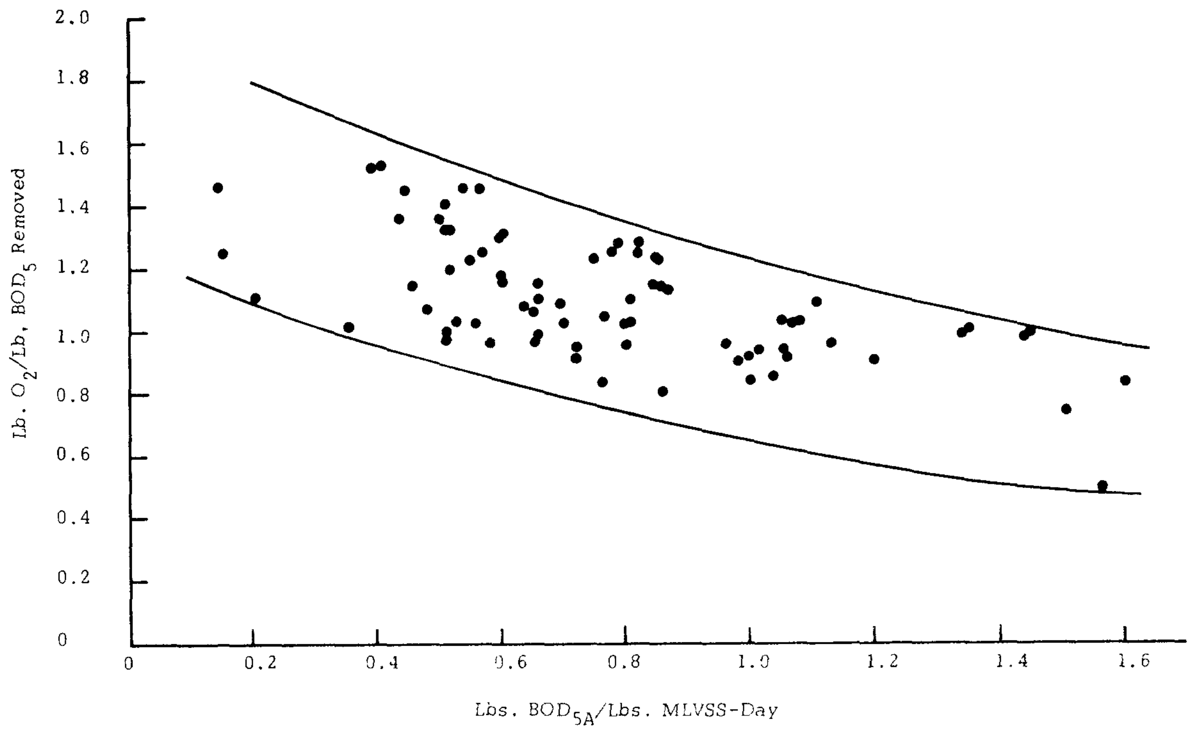

Figure II-4. Unox system, oxygen consumption as a function of F/M.

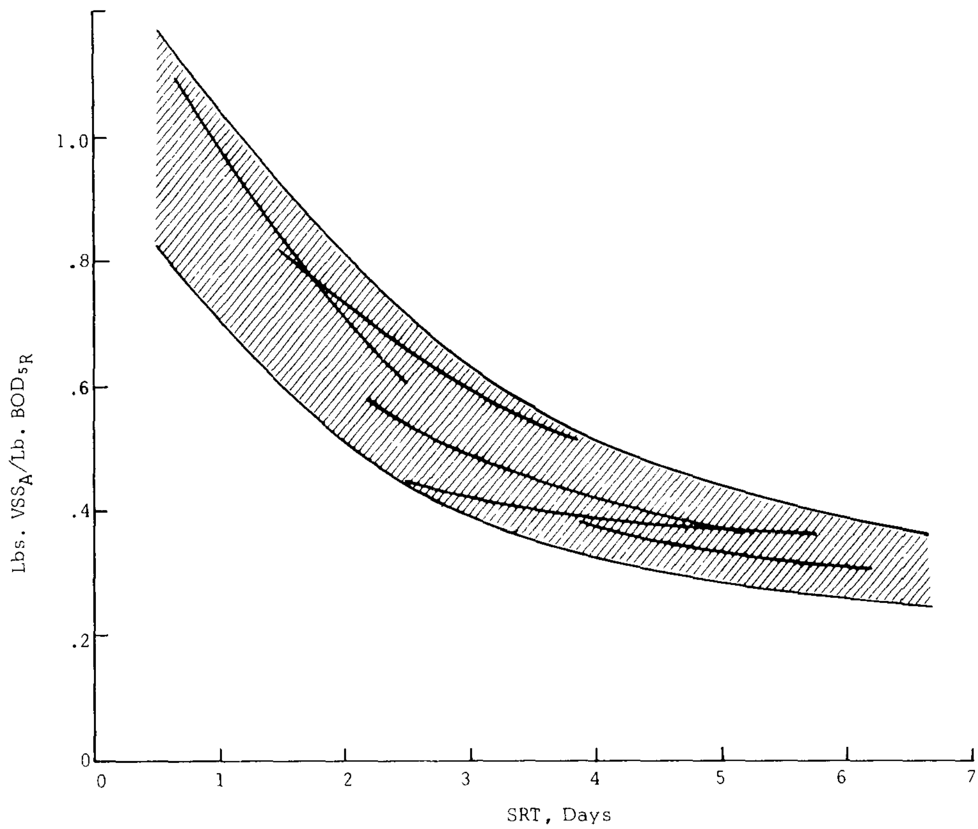

Figure II-5. Unox system, solids accumulation as a function of solids retention time.

It is difficult to correlate excess sludge production for a wide variety of wastewaters, since there are other determining factors to consider when attempting to predict production figures. It is necessary to account for

- The fraction of volatile suspended matter entering the unit that is nonbiodegradable
- The temperature effect on the degree of endogenous respiration
- The quantity of organic material oxidized, not just the BOD_5 removal

These points are in essence the effect of the COD/BOD_5 ratio and, of course, the source of the waste itself. In every instance where Unox and air-activated-sludge systems have been operated side by side, the net solids production from the Unox system has been significantly lower.

Solids-Liquid Separation

The importance of solids-liquid separation to the waste-treatment field cannot be overemphasized. Most often the success of a waste-treatment plant depends on the success of the solids-liquid separation equipment. This statement is especially true for the activated-sludge process, where efficient performance of the final settling tanks is imperative because the solids must be recycled to the aeration basins to sustain the process, and where any solids escaping separation will impair the quality of the effluent.

The performance of the secondary gravity clarifier used in biological-treatment processes, such as in the activated-sludge process, is related to both the physical and chemical nature of the sludge and to the hydraulic characteristics of the clarifier. For the activated-sludge process to be successful, the clarifier must serve the dual function of clarifying the liquid overflow and thickening the sludge underflow. The clarification capacity of the unit is related to the initial settling velocity of the sludge. Conventionally, the area required for clarification of a suspension with hindered settling is estimated such that the vertical liquid-rise rate in the clarifier is less than the solids-subsidence rate over the operating MLSS range. In other words, the allowable overflow rate in this case can be calculated by:

$$OR = \frac{180\ (ISV)}{SF}$$

where

ISV = initial (zone) settling velocity of the mixed liquor, ft/hr

OR = allowable overflow rate, gpd/ft^2

SF = safety factor applied

The area required for sludge thickening, on the other hand, is related to the solids flux or mass loading that the clarifier would be able to handle under gravity. An analysis of the solids flux in a batch-gravity settling tank was given by Kynch. Dick proposed a similar analysis to determine the limiting solids flux in a continuous-gravity thickener or clarifier. In the analyses of both Kynch and Dick, the following basic assumptions were made:

- At any point in the dispersion within the gravity settling tank, the velocity of fall—i.e., the settling velocity of a particle—depends on the local concentration of particles.

- The local concentration of particles is uniform in the radial or horizontal direction or layer.
- Wall effects can be ignored.
- The particles are of the same type.

With the foregoing assumptions, the settling process occurring in the thickening zone of a gravity settling tank can be described using a continuity equation (a solids mass balance in the vertical direction) without knowing the details of the forces acting on the particles.

Assume now that one can express the settling velocity, V_i, solely as a function of solids concentration, C_i, by the following equation:

$$V_i = AC_i^{\,n}$$

where A and n are constants obtained from settling data.

This equation implies that a plot of V_i versus C_i will form a straight line on log-log paper with a negative slope. Some of the settling data presented by Dick seem to support this assumption. To obtain data for Unox systems, a Plexiglass settling column 5½ inches ID by 8½ feet in length was constructed with a stirring mechanism and sample taps along the length of the column, and was used to obtain settling data in many of the demonstration plants. The results of these tests are shown in figure II-6. The band of data for Unox sludges covers a wide range of waste streams in many locations at varying temperatures and biomass loadings. Activated sludge developed in raw degritted wastewater will settle somewhat better than a sludge developed on primary effluent, so the right-hand side of the data band represents raw-wastewater activated sludges or low-VSS/TSS (volatile suspended solids to total suspended solids) sludges. Activated sludges generated from primary effluent wastes will settle with characteristics more typical of the left-hand side of the data band. With these data it is possible to predict closely the expected settling characteristics for a given waste and, therefore, to develop a consistent design for both the biological reactors and the clarifier.

The interaction of the clarifier with the reactor is very critical to the design and reliable operation of any activated-sludge process. The design flexibility is shown clearly in figure II-7, which presents the relationship between clarifier-overflow rate and system-solids concentrations. The figure indicates the trade-offs available to the designer in selecting low clarifier-overflow rates to achieve very high MLSS and recycle-sludge concentrations, or in selecting higher overflow rates with somewhat decreased MLSS and recycle-sludge concentrations. The same figure is also useful in evaluating plant operation as a function of hydraulic cycles, as clarifier-overflow rates change with a corresponding change in system MLSS and recycle-sludge concentrations. Such fluctuations are important design considerations. Figure II-7 is drawn at a constant recycle fraction of 30 percent. A discrete band exists for any recycle fraction. MLSS will increase with increasing recycle ratio (R/Q), while recycle-sludge concentration will decrease.

There is a limited ampunt of initial-settling-velocity data, especially data covering a wide range of solids concentrations for air-activated sludge in the open literature. Katz et al. present a plot of settling rate versus initial solids concentration for an activated sludge without giving any more details. Dick et al. report settling data obtained in three activated-sludge plants, but again no details are given about the plants themselves. Dick also uses a "typical" plot of settling velocity versus concentrations in his illustration problems when he discusses thickening in secondary clarifiers. From these sources we have come up with a range of settling velocities versus concentration relationships that might be representative of the air-activated-sludge-zone settling characteristics. Where the initial settling velocity is plotted against the initial solids concentration for both air and Unox sludges, the Unox sludges have higher initial settling velocity over the entire range of the sludge concentrations of interest (fig. II-6). The general effect on system performance is shown in figure II-8, where MLSS and recycle concentrations are given for typical air and oxygen systems as a function of clarifier-overflow rate.

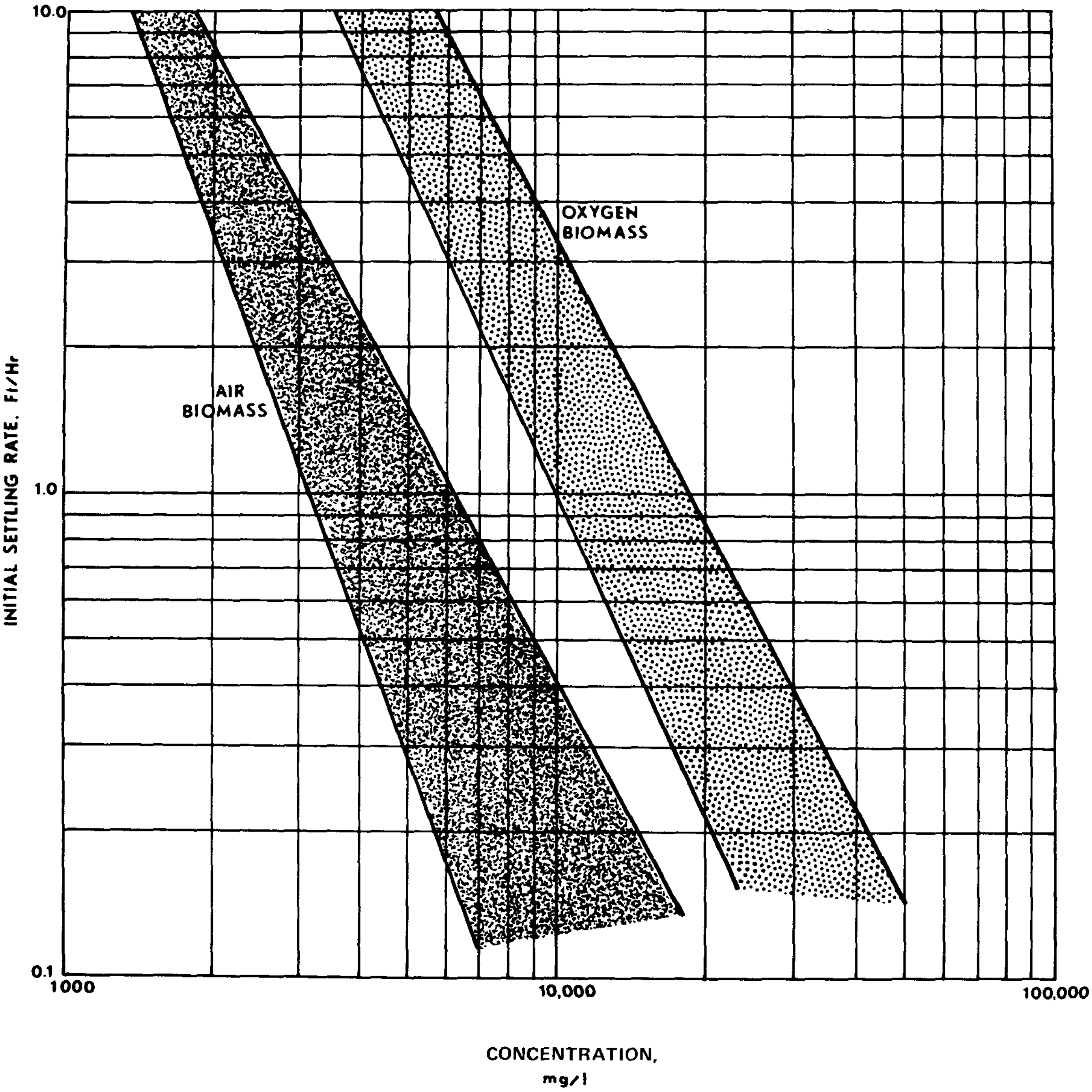

Figure II-6. Settling characteristics for air and oxygen biomass, initial settling rate versus concentration.

The data presented on Unox systems were obtained for biomass developed from primary-effluent wastewaters. The expected settling velocities would be higher than indicated in figure II-6 for biomass developed from degritted wastewater, so that higher MLSS concentrations can be expected than those shown in figures II-7 and II-8 at comparable overflow rates.

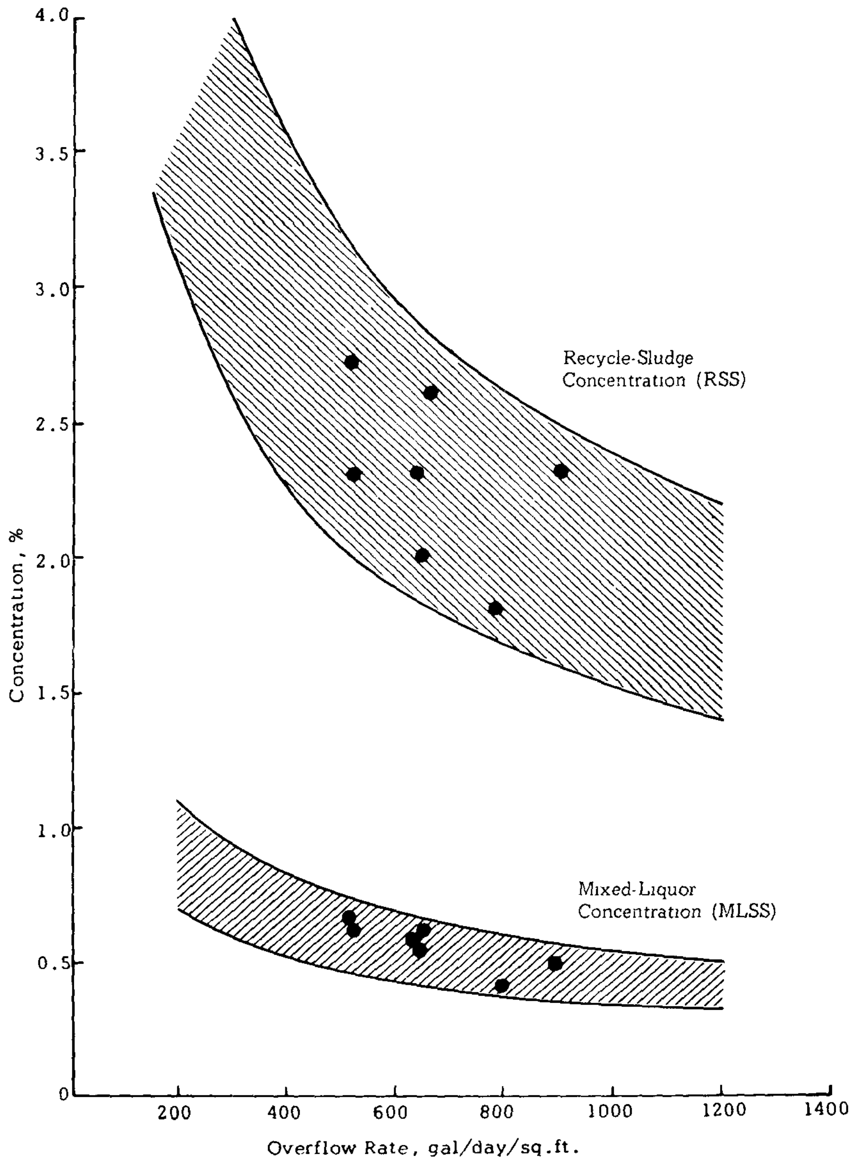

Figure II-7. Predicted secondary-clarifier performance of Unox systems treating primary effluent (at 30% R/Q).

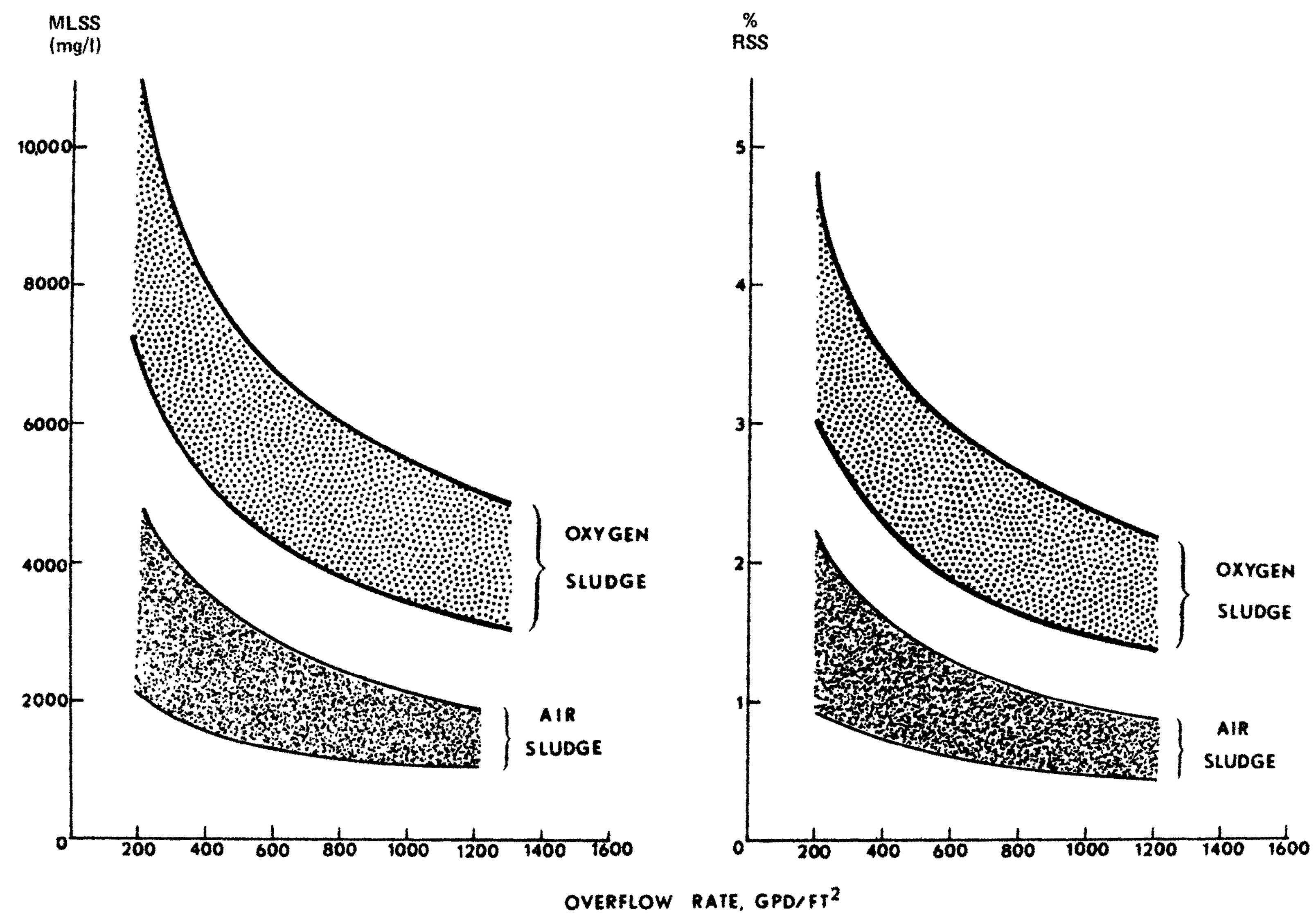

Figure II-8. Typical clarifier performance for air and oxygen sludges (at 30% R/Q).

Chapter III

PROCESS DESIGN

REQUIRED PROCESS INFORMATION

The proper design of any secondary waste-treatment process requires certain basic information concerning the waste to be treated; the Unox system is not an exception. In general, this information can be classified as follows:

- Wastewater quantity
- Wastewater quality
- Effluent quality required
- Definition of the other unit operations or existing facilities in the treatment plant and their relationship to the secondary system

Table III-1 generally shows the required data. The following paragraphs elaborate on each of the foregoing categories and outline the most likely sources of the information. It will be apparent that it is not always possible to obtain all the required information; therefore, it is usually necessary to make some judgments and, consequently, to build some conservatism into the design to account both for inadequate and potentially inaccurate data. The degree of conservatism required, however, can be assessed better by a recognition of those parameters which affect process performance and the resultant appreciation for the quantity of missing information.

Wastewater quantity is, of course, characterized by the rate of flow. Since this rate varies with time it is necessary to have information on the daily diurnal fluctuations as well as on the average and peak flows during the year. This information is generally an extrapolation of existing information into the future and in some instances, where no facilities now exist, for a given facility it is a forecast based on experiences at similar facilities located elsewhere. The information is supplied by the customer's engineer and is used, along with process characteristics, to ascertain a design flow and corresponding peak and minimum flows.

The phrase "wastewater quality" is used herein to describe characteristics of the wastewater that result from the components it contains. The term includes such familiar parameters as BOD_5 and COD. These parameters measure the oxygen requirements of the wastewater. The diurnal variations and annual average and peak values should, therefore, be known in order to quantify accurately the instantaneous and average oxygen demands in the secondary system. These values are also supplied by the customer's engineer and, along with the design flow, serve to define a design loading usually expressed in pounds of BOD_5 per day. Another parameter that helps to characterize the wastewater is the source. Is it municipal, or partially or totally industrial, and what is the industry involved? Also important, especially as it affects the expected settling character of the mixed liquor and the quantity of waste activated sludge for disposal, is the treatment preceding the secondary system. If the waste is only degritted the MLSS will settle better and will contain a lower volatile fraction than if the waste has received primary settling. Also, more waste

Table III-1.—*Definitional parameters*

Wastewater quantity: maximum month-design year	Wastewater quality	Required effluent quality	Site limitations	Solids-handling equipment	Secondary-clarifier specifications
Average flow, mgd	Average BOD_5, mg/l	BOD_5, mg/l	New or existing tankage	Dewatering	Overflow rate at design flow, gpd/ft^2
Maximum 4-hour sustained peak flow, mgd	Maximum sustained (coincides with maximum flow), mg/l	Suspended solids, mg/l	Land area available	Sludge disposal	Depth, feet
Design flow, mgd	Design BOD_5, mg/l	N, mg/l	Piling required		Feed
	COD/BOD_5, all cases	P, mg/l	Maximum tank depth, feet		Takeoff
	Source	COD, mg/l			Sludge return
	Preceding treatment				Circular or rectangular
	Average suspended solids, mg/l				
	Average volatile suspended solids, mg/l				
	Temperature, °C				
	pH				
	Alkalinity, mg/l as $CaCO_3$				
	Alpha, beta				
	Nutrient content, mg/l N, P				
	Heavy metals				
	Other toxic components				

sludge will leave the secondary system if no primaries exist. Other important quality parameters are temperature (average and range), pH, alkalinity, TSS and VSS level, alpha and beta values for the sewage, nutrient content, and the expected concentration of heavy metals or other components potentially toxic to the secondary-system biomass. The above parameters are also to be supplied by the customer's engineer. Specifications for final settling tanks are listed in appendix A.

Another quality parameter best determined by pilot-plant operation is the oxygen consumption requirements in terms of the amount required for biomass synthesis and endogenous metabolism, both of which occur during the removal of the pollutant material. In many cases, the waste stream does not exist presently, or it is known that additional streams will alter its character in the near future, so that pilot-plant results would not necessarily be representative of those to be expected in full-scale operation. It is in situations such as these that the very large amount of Unox-system pilot-plant data on a variety of waste streams becomes especially useful. As can be seen from figure II-4, the oxygen consumption requirements are related to the F/M ratio.

The same discussion used in regard to the oxygen requirement also can be used to describe the mixed-liquor settleability and the biokinetic characteristics of the wastewater, which also must be known and can be determined best from pilot-plant data. These characteristics, too, can be estimated based on broad pilot-plant experience and the known source of the wastewater (see fig. II-6 for settleability).

The effluent quality required is defined by the customer or his engineer, and is usually based on receiving-stream standards or State regulations for removal. Parameters such as BOD_5, suspended solids, TKN, and phosphorus usually are involved. This required effluent quality must, of course, be known by the designing engineer, as it dictates the extent of the required treatment. In the extreme, it may not be possible to attain the required effluent quality with a secondary system, in which case some form of additional treatment would be required.

The remaining required information pertains to specific site limitations and to prior and subsequent unit operations that the customer's engineer is planning to specify. Required site-limitation information includes whether the job is to convert existing tankage to upgrade the plant capacity or to install new tankage. Also, it must be known whether land area is limiting, and what limitations must be placed on tank depth and area due to water table level and piling requirements. The prior and subsequent unit operations are important in that they influence the character of the waste fed to the secondary system. Most sludge-handling systems have supernate streams that are returned to either the primary or secondary systems and, depending on the system in question, these streams may have a noticeable effect on the character of the waste entering the secondary system.

The secondary clarifier is of extreme importance in the operation of a secondary treatment system. The designer of the secondary system must know the overflow rate, depth, feed mechanism, takeoff mechanism, and sludge-return mechanism that the customer's engineer intends to install. The Unox system will perform well with the same clarifiers that are used for a conventional air system; but since the clarifier itself has such an important effect on the expected underflow concentration and the MLSS concentration, its design must be known so that the Unox system can be properly integrated with it.

OXYGENATION TANKAGE DESIGN

The first major step in preparing a process design for a Unox system lies in the selection of what may be termed "independent variables." These variables may be called independent because selection of one does not reduce automatically the freedom of selection of the others due to the interrelationships in the process. The basic independent design variables are

- Clarifier overflow rate
- Recycle ratio
- Food-to-biomass ratio
- MLVSS (mixed-liquor volatile suspended solids) concentration
- Aeration-tank geometry

For conventional gravity secondary clarifiers, the MLVSS concentration is, of course, related directly to the secondary-clarifier design. The sludge-settling characteristics, the clarifier-overflow rate, and the recycle fraction directly determine the MLVSS levels attainable in the oxygenation tank, as discussed earlier.

The food-to-biomass ratio initially is selected at a value at which the system will operate properly in terms of required removals, both at design and sustained-peak loadings. The range of food-to-biomass ratios under which Unox systems have been run at high removal efficiencies on a variety of wastes is shown in figure II-2. The design-level food-to-biomass ratio is selected such that the sustained peak food-to-biomass ratio lies within the range of proven operation. Typically, the peaks and design points will be such that the design food-to-biomass ratio is between 0.5 and 0.8. Following selection of the food-to-biomass ratio at the design point, it remains only to determine the MLVSS level to have dictated the required aeration-tank volume. This MLVSS level (used as a measure of the viable organisms in the mixed liquor) is, of course, dependent on the total MLSS level, which, in turn, is dependent on the clarifier-overflow rate, recycle ratio, type of waste, and type of pretreatment. Figure II-8 shows the expected clarifier-underflow concentrations for Unox systems as a function of overflow rate at a given recycle ratio. As discussed earlier, the type of waste and the pretreatment received will dictate where within the band of expected underflow concentration the case under consideration will fall. Once an R/Q has been specified and a value of underflow concentration determined, MLSS level is determined by material balance (ignoring influent solids and the net solids production within the aeration tanks relative to the amount of solids present in the recycle stream) (see fig. II-7).

The recycle ratio is selected as follows. The higher the R/Q, the higher the mixed-liquor-solids concentration will be (up to about 100 percent recycle); but the clarifier-underflow concentration will be correspondingly lower and the subsequent treatment of the waste activated sludge correspondingly more difficult. The recycle ratio should be selected to maximize the MLSS concentration, recognizing that clarifier-underflow concentration will diminish as recycle fraction increases. A value of 0.3 for the recycle ratio typically is selected for a Unox-system design.

Once the MLSS concentration has been determined, the volatile fraction must be ascertained in order to specify the system volume. Pilot-plant data are the best source for this information; and, as can be seen from tables II-3 to II-7, values for degritted waste can vary from 0.66 to 0.83, and for primary-treatment waste from 0.72 to 0.90. In the absence of specific pilot-plant data, and due to the large quantity of Unox-system pilot-plant data, a good judgment as to the expected value for the volatile fraction can be made by knowing the waste source.

Knowing the design-point BOD_5 load, food-to-biomass ratio, and MLVSS level, the detention time (based on raw flow) is fixed and, given the design flow, so is the oxygenation-tank volume. With the information in hand concerning land-area restriction, piling requirements, restrictions imposed by existing tankage, and so forth, the economic tank depth can be ascertained. Thus, the area of the tankage is determined, and it remains only to specify the number of parallel bioreactors and the number of stages per bioreactor to have specified completely the oxygenation tankage. Generally, at least two parallel bioreactors are used with at least three stages per bioreactor.

Specifications for oxygenation tanks are listed in appendix B.

OXYGEN REQUIREMENTS

As mentioned earlier, the oxygen requirements for a Unox system depend on both the COD/BOD_5 ratio of the feed wastewater and the food-to-biomass ratio under which the system is to operate. Figure II-4 depicts the quantitative dependence on F/M as determined from the many pilot-plant programs. Given the value of the COD/BOD_5 ratio and the food-to-biomass ratio as previously specified, it is possible to determine the expected consumption ratio (pounds of oxygen consumed per pound of BOD_5 removed) for the wastewater to be treated. Given the design flow, BOD_5-feed concentration to the secondary system, and required removal, the pounds of oxygen consumed per day are determined. If (as is typically the case from economic considerations) about 90 percent utilization of the oxygen is specified, the tons per day of oxygen that must be generated at the design point are fixed.

OXYGEN SUPPLY

Following determination of the quantity of oxygen that must be generated to satisfy the wastewater demands, it is necessary to specify the type of oxygen generator that best will serve the needs of the plant. Two basic oxygen-generator designs are employed to supply most economically and practically the wide range in oxygen demands that result from the wide range in size of wastewater-treatment plants. These designs are the traditional cryogenic air-separation process for the larger size applications and a pressure-swing adsorption (PSA) system for the somewhat smaller and more common plant sizes.

The standard cryogenic air-separation process involves the liquefaction of air, followed by fractional distillation to separate it into its components (mainly nitrogen and oxygen). Figure III-1 shows a schematic diagram of this process. The entering air is first filtered and compressed. It is then fed to the reversing heat exchangers, which perform the dual function of cooling and removing the water vapor and carbon dioxide by freezing these mixtures out into the exchanger surfaces. This process is accomplished by periodically switching or reversing the feed air and the waste nitrogen streams through identical passes of the exchangers to regenerate their water vapor and carbon dioxide removal capacity. The air is next processed through "cold and gel traps," which are adsorbent beds that remove the final traces of carbon dioxide as well as most hydrocarbons from the feed air. It is then divided into two streams, one of which feeds directly to the lower column of the distillation unit. The other stream is returned to the reversing heat exchangers and partially warmed to provide the required temperature difference across the exchanger. This stream is then passed through an expansion turbine and fed into the upper column of the distillation unit. An oxygen-rich liquid exists from the bottom of the lower column and the liquid nitrogen from the top. Both streams are then subcooled and transferred to the upper column as shown in figure III-2. In this column the descending-liquid phase becomes progressively richer in oxygen until that which collects in the condenser reboiler is the oxygen-product stream. This oxygen is recirculated continually through an adsorption trap to remove all possible residual traces of hydrocarbons. The waste nitrogen exists from the top portion of the upper column and is heat exchanged along with the oxygen product to recover all available refrigeration and to regenerate the reversing heat exchangers as discussed in the foregoing.

The cryogenic process is more economical for supplying more than 30-50 tons of oxygen per day. The process can be supplied by at least three companies on a performance specification with

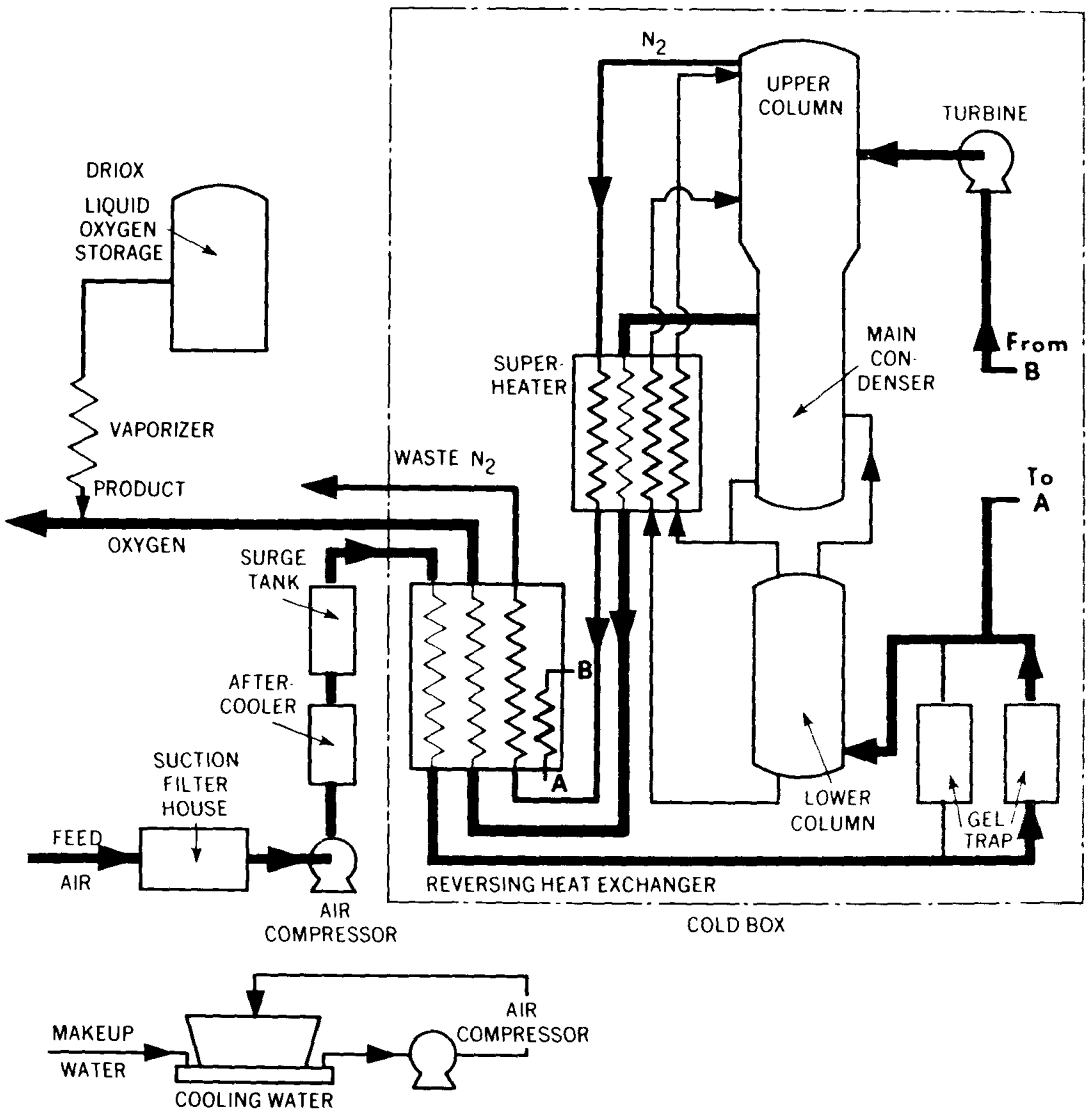

Figure III-1. Flow diagram of a cryogenic oxygen-generating system.

quality requirements; it can be considered best as a "black box" piece of equipment, except as its characteristics affect design of the wastewater-treatment plant. The performance specification is similar to those for blowers, pumps, and so forth.

Cryogenic oxygen plants can be turned down to approximately two-thirds full capacity, which, by coincidence, happens to be a normal turndown for large compressors. If all of the two-thirds plant capacity cannot be used, then the oxygen must be wasted to atmosphere through a stack.

A full standby for the primary compressor should be provided. At the Middlesex County Sewerage Authority (in New Jersey), for a 400-ton-per-day plant, the centrifugal compressor with adjustable-inlet guide vanes will be driven by an 8,000-hp electric motor. The demand charges for running two compressors while changing from one to the other was so great that one compressor will be taken offline before the second is started. This practice will result in up to 2 hours of lost oxygen production. A full standby should also be provided for the turbine expander, which is another large motor.

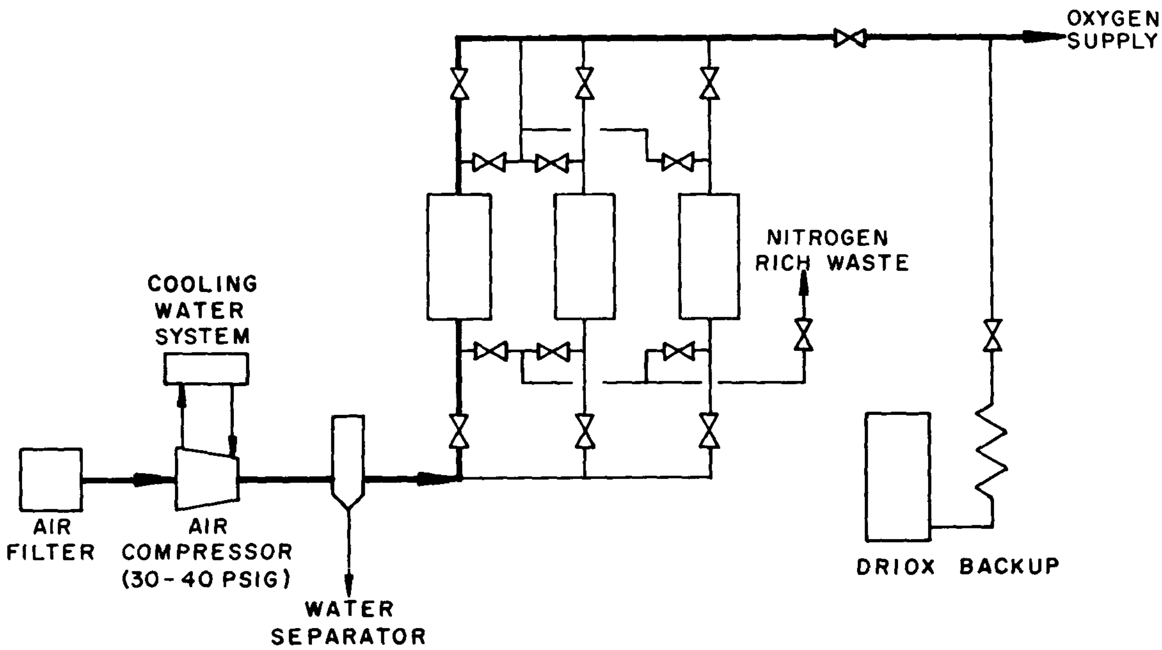

Figure III-2. Pressure-swing adsorption oxygen generator for Unox systems.

All pipes and equipment containing, processing, or transporting liquid oxygen (LOX) or nitrogen are very cold and must be well insulated; otherwise ice will build up from the freezing of condensed atmospheric water vapor at any point not insulated.

Cryogenic gas oxygen will cost municipalities approximately \$8 per ton (capital, operation, and maintenance) at capacity production. LOX costs approximately \$35 per ton.

Cryogenic plants must be shut down for a period of 5-10 days once every 1½-2 years for deriming (cleaning). A cryogenic plant can produce LOX or gaseous oxygen (GOX), or various combinations of the two, depending on how it is designed. Each ton of LOX produced will reduce GOX by about 4 tons.

A cryogenic plant takes 1-3 days to start up, depending on whether LOX is available or not. It is not practical to meet variable demands by starting and stopping cryogenic units.

Dividing a cryogenic demand into two or more plants can help to meet economically the demands of a wastewater-treatment plant at the beginning and end of the design period if it is serving a rapidly growing service area, but such division will not be useful for unpredictable variations.

The PSA system employs a multibed adsorption process to provide a continuous flow of oxygen gas. Figure III-2 shows a schematic diagram of the four-bed embodiment. The feed air is compressed and passed through one of the adsorbers. The adsorbent removes the carbon dioxide, water, and nitrogen gas, producing relatively high-purity oxygen. While one bed is adsorbing, the others are in various stages of regeneration. The PSA oxygen generator operates on a PSA concept in which the oxygen is separated from the feed air by adsorption at high pressure (30-60 psig) and the adsorbent is regenerated by "blowdown" to low pressure. The process operates on a repeated cycle having two basic steps, adsorption and regeneration. During the adsorption step, feed air flows through one of the adsorber vessels until the adsorbent is partially loaded with impurity. At that time the feed-air flow is switched to another adsorber and the first adsorber is regenerated. During regeneration the impurities are cleaned from the adsorbent so that the bed will be available again for the adsorption step. Regeneration is carried out by depressurizing to atmospheric pressure, purging with some of the oxygen, and repressurizing back to the pressure of the feed air.

As discussed earlier, the driving force on the oxygen-gas generator is a simple, relatively low-horsepower air compressor. An obvious and totally acceptable form of overall system backup would, therefore, be a spare feed-air compressor, which would supply essentially 100 percent backup capability. A more desirable, effective, and flexible form of oxygen-supply backup, however, can be obtained through the use of onsite LOX storage in conjunction with the onsite gas generator. This backup is in the form of from one to several days' production capacity of LOX storage. This method not only provides absolutely failsafe backup to the onsite oxygen-gas generator, but it also adds the capability of instantaneous delivery of substantial additional oxygen capacity to the aeration tanks to handle peak-load conditions. Such peak or above-average loads otherwise could be handled only by substantially oversizing the oxygen generator.

The PSA process is more economical for less than 50-30 tons of oxygen per day. PSA oxygen generators produce oxygen of 88-90 percent purity. Three or four absorption units are used to permit continuous oxygen production. In comparison with cryogenic units, the oxygen is less pure, but the unit turndown is limited only by the compressor capacity. Because of their turndown characteristics and the partial load under which most oxygen generators will work, the PSA units are more economical at higher oxygen capacities than would be expected by comparisons made for capacity production.

The PSA generator employing four adsorption units uses 24-30 valves, most of which are operating every 2-5 minutes. The dependability of these valves is of paramount importance—if one valve malfunctions, the entire unit shuts down. The possibility has been considered of providing an extra adsorption unit that could be used to replace a malfunctioning unit; however, the interrelationship of the four units and the 24-30 valves makes this difficult. Standby is provided from LOX storage.

Both PSA and cryogenic plants have efficient turndown capability, with the PSA units being capable of turning down with only a small loss in efficiency throughout the entire range of their production capacity. Although the cryogenic plant cannot turn down as far, it does have the capability to produce LOX during low-load periods. This liquid can be stored and used to supplement the plant during periods of high load. Therefore, although the cryogenic plant cannot turn down all the way, it can be installed at a capacity somewhat less than the sustained peak would demand.

OPERATING-POWER REQUIREMENTS

Given the basic gas-liquid mass-transfer capabilities for the dissolution equipment selected, the operating horsepower for oxygen transfer can be determined for the oxygen-gas-phase concentrations, oxygen-consumption requirements, wastewater alpha and beta values, temperature, and operating DO level. The gas-phase concentration varies throughout the system, with the highest concentration (highest transfer driving force) present at the front end of the system where the highest demand exists. Thus, in comparison with air systems, a fourfold to fivefold increase can be attained in the latter stages where the gas is vented at 40-60 percent oxygen concentration.

Once the dissolution-power requirements have been determined, a check should be made to be sure that sufficient energy is supplied with the selected dissolution equipment to maintain proper mixing biomass in suspension. Generally speaking, if the equipment can maintain sufficient bottom velocities throughout the tank, mixing should be adequate. If it is found (as will often be the case with a weak waste) that sufficient bottom velocity will not be maintained, additional horsepower must be added; the system then is said to be mixing limited. Brake-horsepower requirements for dissolution and mixing in a Unox system typically run from 0.08 to 0.14 hp per 1,000 gallons of mixed liquor under aeration, depending on the waste strength, the degree of mixing limitation, the feed-oxygen purity used, and the mass-transfer capability of the dissolution equipment.

SUSTAINED PEAK LOADS

Most waste-treatment plants experience, a few times during the year, waste loads that can be described as the "sustained organic peak loading." This loading is the maximum organic loading (pounds of BOD_5 per day, includes the combination of flow and concentration) which the plant sees for a sustained period, usually in excess of 4 hours. As 4 or more hours are sufficient to "upset" the system for substantially longer than the period of occurrence if essentially zero-DO conditions prevail in the oxygenation tanks, the oxygenation system should be designed to maintain 1-2 mg/l of DO in the system in the first stage during these peak-organic-loading periods. The Unox system has several inherent characteristics that allow it to handle these peak conditions. At peak-load conditions, Unox systems are designed to maintain approximately 6 mg/l DO in the mixed liquor. In the event of an unusually severe, short-duration peak, the ability to transfer about 30 percent more oxygen into the mixed liquor is achieved if the DO level decreases to 1-2 mg/l. Also, because LOX is available for backup purposes with the same supply capacity as the installed plant, it is possible to double the oxygen-plant flow to the oxygenation tankage. Assuming the oxygen plant is designed to supply enough oxygen for the sustained peak condition with 90 percent utilization, it is therefore possible to decrease the utilization to less than 50 percent. This decrease results in a much-increased average oxygen-gas-phase concentration with a resultant increase in dissolution capacity. Although this mode of operation is not economic over extended periods of time, for the short term it can be quite effective.

Both of these methods for increasing dissolution capacity function by increasing the driving force for mass transfer. The first reduces the mixed-liquor DO, while the second increases the oxygen-saturation concentration in the mixed liquor. Neither option is available to an air system, since the design DO level is usually already at 1 or 2 mg/l and the oxygen concentration of air is fixed.

As the load on a plant increases, the food-to-biomass ratio increases at least proportionately. If only the BOD_5-concentration increase is responsible for the peak condition and the flow remains the same, the MLVSS level will remain substantially the same and the food-to-biomass concentration will indeed increase by the same amount as the organic load. If, as is more commonly the case, the increase in organic load is a result of both flow and concentration increases, or of flow increases alone, the clarifier-overflow rate will increase and the MLSS level will decrease. This effect results in a food-to-biomass ratio that is increased by some amount greater than the increase in organic load. Due to the ability of the Unox system to obtain good removals over such a wide range of food-to-biomass ratios (see fig. II-2), this increase in food-to-biomass ratio will not be detrimental to system performance as long as the required oxygen can be supplied. As can be seen from figure II-4, however, an increase in food-to-biomass ratio can result in a substantial decrease in the oxygen required per pound of BOD_5 removed as more biomass is formed and less endogenous respiration occurs.

With the capability to transfer more oxygen than at the design point, and considering that a decrease in consumption ratio usually occurs at the sustained peak condition, the Unox system has the capability to handle organic loads from 2 to 2½ times the design organic loading while still maintaining completely aerobic conditions in the aeration tankage.

ACTIVATED-SLUDGE-WASTE QUANTITY

The two parameters of major importance in sizing of sludge-dewatering and solids-disposal systems are the pounds of waste solids per day and the concentration of solids in the waste stream. The former obviously indicates the solids that must be disposed of, while the latter is indicative of the volume of waste that must be treated. The pounds of solids that must be wasted per day to prevent accumulation in the system is dependent on several parameters. The biomass is producing new biomass in the process of removing BOD_5. The ratio of the biomass synthesized to the BOD_5 removed is known as the yield coefficient. Endogenous respiration is also occurring at a rate proportional to the number of viable organisms in the mixed liquor, resulting in the destruction of some of the organisms. Since the endogenous respiration is proportional to that fraction of the MLVSS that is active biomass, the percentage of active biomass in the mixed liquor will be, in part, dependent on the stresses put on the system. Thus, maintenance of relatively constant environmental conditions should result in an increased fraction of active biomass and, thus, less overall sludge production. The maintenance of relatively constant environmental conditions is, of course, an inherent characteristic of a Unox system.

Other parameters affecting the quantity of solids that must be wasted from the system are the quantity of nondegradable solids (both volatile and nonvolatile) that enter the system with the influent sewage, and the quantity of solids that leave the system in the effluent stream. Therefore, the pounds that must be wasted from the system are the pounds produced by synthesis during BOD_5 removal, plus the pounds entering the system as nondegradable-volatile and nondegradable-nonvolatile solids, minus the solids destroyed by endogenous respiration, minus those lost from the system in the effluent.

Figure II-5 indicates the pounds of excess volatile solids formed per pound of BOD_5 removed as a function of sludge retention time (sludge age) as observed at several Unox-system pilot-plant locations. The results include the effect of temperature (some plants were run in the South in summer, with resulting low production, and others in the North in winter, with higher production), variations in nondegradable volatile solids in the influent from plant to plant, as well as the yield and endogenous decay effects. Given the desired SRT, the temperature of interest, and the expected quantity of nondegradable volatile solids in the influent sewage, it is possible to estimate from figure II-5 the pounds of excess volatile suspended solids that will be produced. Given this estimate, the expected suspended solids in the effluent, and the ratio of the volatile suspended solids to the total (see tables II-3 to II-7), the pounds of solids that must be wasted daily can be estimated.

It remains to determine the gallons per day of the waste stream, which can be done given the information previously presented. The clarifier-underflow concentration was determined in assigning the mixed-liquor-suspended-solids level. This concentration of the waste stream and the pounds of solids wasted per day fixed the gallons wasted per day. A highly concentrated waste stream, such as the one that can be obtained from a Unox-system sludge, can have value in decreasing the costs associated with sludge handling and disposal.

Chapter IV

PROCESS SAFETY

OXYGEN GAS

In a Unox system, oxygen is delivered to the system in a relatively pure form, and contact with the mixed liquor takes place in a closed system. For these reasons, a few routine safeguards are necessary to insure a totally safe wastewater-treatment system.

Oxygen itself is not dangerous; it is colorless, odorless, and tasteless, and it supports combustion. A flame burning in pure oxygen combusts at a more rapid rate than in air because of the absence of nitrogen as a diluent. It is a common fallacy that the combination of oxygen and combustible material will spontaneously ignite. The lower explosive limits (LEL) of all commonly found hydrocarbons are almost exactly identical in an oxygen or air atmosphere. Furthermore, for ignition to take place a spark must be present; autoignition does not occur. Thus, the safeguards built into a Unox system are not to protect against oxygen gas, which is not dangerous by itself, but to prevent a buildup of combustibles in the gas space in the covered aeration basin.

OXYGEN AND THE UNOX SYSTEM

LOX is stored at a few inches of water pressure in highly insulated steel tanks. Approximately 5 days of storage are provided. The heat gain into the storage tanks is met by evaporation of approximately 0.2 to 0.4 percent of the LOX per day.

The LOX storage tanks should be surrounded by a dike that will hold the entire contents of the tanks. In the extremely unlikely chance that the LOX storage tank ruptures or leaks, the LOX will evaporate rapidly and be discharged into specific gravity of 32, compared with air at 29, so that it is only slightly heavier than air and will dissipate easily. In case of a large spill the GOX will be very cold and will tend more to stay on the ground and not mix.

Oxygen enters the oxygenation tank, where a gage pressure of 1-4 inches of water is maintained, and mixes with the wastewater. After entering the oxygenation tank, the high-purity gas (90-100 percent oxygen) passes through a series of wastewater-treatment stages and is vented to the atmosphere with approximately a 40-50-percent oxygen concentration. The process gas in the aeration tank presents a safe environment because it is at low pressure (several inches of water), ambient temperature, and is saturated with water vapor.

All equipment and materials having to do with the storage and handling of oxygen are selected carefully for oxygen compatibility. In this connection, the mechanical, electrical, and control equipment are located in the open atmosphere, avoiding the high-oxygen concentrations under the tank cover. Because of the low pressures in the process, it is highly unlikely that an oxygen leak could create a hazard to equipment or personnel by creating high-oxygen concentrations.

The pumps used to move the LOX are critical. They must be kept as cold as the LOX. LOX could be moved through the evaporators and to the oxygenation tanks by maintaining a small pressure in the LOX-storage tanks. The PSA system cannot produce LOX. Therefore, the LOX storage must be refilled from time to time by purchased LOX, which can be delivered in rail tank cars or trucks (at $35-$40 per ton).

The possible presence of combustible materials in wastewater from gasoline or oil spills and industrial-plant upsets is well known to treatment-plant operators. Although such spills may occur, dangerous volatile hydrocarbons are not expected to reach the Unox system for several reasons. These materials are only sparingly soluble in water and tend to be stripped easily from the wastewater by contact with the atmosphere. Volatile materials such as gasoline, therefore, normally would be stripped from the wastewater in the sewer lines before entering the treatment plant. At the treatment plant itself, these volatile materials would be removed further in existing comminutors, screen chambers, grit chambers, or primary clarifiers before entering the Unox system.

The presence of volatile hydrocarbons in the oxygen-rich gas space of the Unox-system aeration tank is not a sufficient condition to constitute a hazard; a source of ignition is also required. The Unox-system components are designed to eliminate any potential ignition sources. As discussed earlier, no electrical components are installed under the tank cover, and no metal-to-metal contact of moving parts is present.

Even though both an ignition source and a fuel in concentrations exceeding the LEL are required for a hazard to exist, it is the policy in designing a Unox system to eliminate both. To this end, combustible gas analyzers are employed in the aeration tankage to monitor continuously the process gas for the presence of combustible material. Should an approach to an LEL limit occur, the analyzer activates the necessary controls that cause the gas space to be purged with air, thereby preventing a buildup of the combustible vapors to a level greater than 50 percent of the LEL. The purging continues until the gas and liquid have carried the combustible material out of the system.

Greases and oils are also commonly present in both municipal and industrial wastewaters. These substances have low volatility at wastewater temperatures and pass through the system with as much bio-oxidation and decomposition as are normally obtainable in a biological treatment process. Greases and oils are not combustible under these conditions.

Chapter V
UNOX-SYSTEM SCOPE OF SUPPLY

GENERAL

In general, the scope of supply for a Unox system includes oxygen-dissolution equipment, oxygen-generation equipment, and appropriate controls and instruments to mate the two subsystems in an efficient, reliable, and safe operating mode. The scope of supply does not include concrete work, deck covers, or, in many cases, installation of the foregoing equipment. All engineering work necessary to design and provide a workable Unox system is performed in cooperation with the customer and/or his consulting engineer.

The Unox-system dissolution equipment will be, in general, either surface aerators or submerged turbines, depending on economic considerations. Generally speaking, where deep tanks offer an advantage over shallow, and where the waste stream is large in quantity and high in strength, a submerged-turbine system will be preferable. Therefore, again in the general case, it can be expected that the greatest number of Unox systems will employ surface aerators while the largest sized applications may well use submerged turbines. Because of the complexity inherent in large jobs, it is often the policy to offer these Unox systems on "installed by UCC" terms, while the smaller jobs can be more cost effective on uninstalled terms. As has been mentioned earlier, the cryogenic-oxygen supply is often more cost effective for large plants, and the PSA for smaller ones. The most common combinations will therefore be surface aerators with PSA oxygen and submerged turbines with cryogenic oxygen. The following paragraphs outline a typical scope of supply for each of these combinations with the surface-aerator-PSA combination preceding the submerged-turbine, cryogenic-oxygen combination.

SURFACE-AERATOR-PSA SYSTEM

Dissolution Equipment

The number of units specified in the design will be supplied. Each will be designed to be assembled as a complete unit ready for installation through openings in the tank covers. Each assembly will consist of the following:

- Motor, speed reducer, and lube system
- Shaft and aerator blade
- Mounting skid and shaft seal

All equipment and materials are designed to provide long, maintenance-free service. The speed reducers are specified to have an overall AGMA service factor of 2, while other components critical to the continuous operation of the assembly are designed for service factors of up to 5. Gearing and bearings of proven quality are used throughout the speed-reducer assembly. The gearing has a service factor of 2 plus 200 percent overload-rating capabilities. The antifriction bearings are designed to the AFBMA (B-10) life rating of 75,000-100,000 hours, depending on the severity of the application. All components submerged in the mixed liquor are made of stainless steel or other materials proven to give prolonged service in the mixed-liquor environment.

PSA Equipment

The oxygen-generation plant is an automatically controlled unit. It is made up of an adsorption unit and a compressor unit. The adsorption unit is designed as a complete package containing adsorbent vessels, valve-and-piping skids, and controls. The vessels contain sufficient adsorbent, supplied by Union Carbide, to upgrade air to the desired purity. The vessel design is such as will minimize air losses.

The valve-and-piping skid contains pneumatically operated automatic valves mounted directly on the skid. The valves selected have been demonstrated to be leaktight after 1-2 million cycles. In addition, the PSA skid contains all necessary valves and controls required for flow and pressure control. It also contains local instrumentation.

An air drier is provided to dry the air used for the instrumentation. This drier is mounted on the PSA-unit skid, is suitable for outdoor installation, and is capable of automatic operation.

The compressor unit is completely assembled on a common skid and ready for immediate mounting on a concrete foundation. This skid assembly includes a nonlubricated compressor, electric-motor driver, aftercooler, moisture separator, discharge-pulsation dampener (if required), inlet air filter, high-discharge temperature- and pressure-shutdown switches, lube system, and all interconnecting piping and valves. A separate skid contains the cooling system. The equipment provided is of the highest quality and is designed to operate for many years with only routine maintenance. It is also suitable for unprotected outdoor installation, and includes any special protection or provisions necessary to provide continuous year-round operation.

SUBMERGED-TURBINE-CRYOGENIC SYSTEM

Dissolution Equipment

The oxygenation tanks will be fitted with the number of mixing and oxygen-dissolution assemblies specified in the design. Each mixing assembly consists of an electric-motor-driven speed reducer, propeller, and gas injection sparger totally integrated and assembled to a base plate that bolts to the tank cover. All equipment used is designed to provide long, maintenance-free service. The speed reducers are specified to have an overall AGMA service factor of 2, while other components critical to the continuous operation of the mixing assembly are designed for service factors of up to 5. Gearing and bearings of proven quality are used throughout the speed reducers. The gearing has a service factor of 2 plus 200 percent overload-rating capabilities. The antifriction bearings are designed to the AFBMA (B-10) life rating of 75,000-100,000 hours, depending on the severity of the application. All components submerged in the mixed liquor are made from stainless steel or other materials proven to give prolonged, trouble-free service in the mixed-liquor environment. The entire mixing and oxygen-dissolution assembly is instrumented with simple but reliable monitors that will set off an alarm in case of potential problems and/or shutdown equipment before any component failure has taken place.

The oxygen-gas injection to the mixed liquor is accomplished by low-pressure oxygen compressors. These machines can be located on the tank covers, either outdoors or in a small building provided on or near the tanks. Each compressor is manifolded to deliver oxygen gas to all similar stages in the tanks. The compressors are designed to the same high standards as the mixing assemblies and are instrumented similarly to warn of possible impending problems. Automatic shutdown of any unit is provided before extensive damage can occur to the machinery. Automatic shutdown of equipment is a feature afforded only in the Unox system, since process backup is provided by the other equipment on stream.

Cryogenic-Oxygen-Generation Plant

The oxygen-generation plant is an automatically controlled unit. It is composed of the following major components:

- Air-suction filter house
- Centrifugal air compressor, driven by an electric motor, with interstage cooling after each stage
- Air-surge tank to absorb the cyclic variation in air flow to the reversing heat exchangers
- Air-separation unit or cold box consisting of a column and reboiler, gel traps and superheater, and reversing heat exchangers—cryogenic equipment installed in cylindrical casings fabricated from carbon steel, perlite insulated, and maintained under a slight positive pressure to prevent moist air from entering the insulation space; cold box factory fabricated with most internal parts made of aluminum
- Cryogenic expansion turbine—process air admitted radially inward through variable-area nozzles, expanded in the turbine impellers, and exhausted axially; the impeller shaft directly connected to the blower; turbine-seal-gas system, the turbine-lube-oil system supplied with the turbine; oil temperature controlled, and backup for turbine coastdown supplied by an oil-filled, pressurized accumulator
- One thaw heater assembly to thaw the cryogenic cold box, including gel traps during turnarounds
- Cooling tower to supply required intercooler, and aftercooling of the gas leaving the air compressor

In addition to the foregoing major components, all the instruments, piping, controls, and instrument panels necessary to make this plant functional are included.

INSTRUMENTATION

An integrated-control system is included, which automatically controls the oxygen-gas flow to match the demand of the oxygen load on the system. The oxygen-generating plant increases or decreases its output automatically in response to the system.

A main panel is supplied with a vent-gas analyzer and indicator, a combustible-gas analyzer and recorder, a feed-gas-flow controller, and a central alarm that will sound in case of an impending malfunction of the unit.

Stage pressure/vacuum relief devices are provided, as are appropriate shutdown switches for the mechanical equipment.

OXYGEN-BACKUP FACILITIES

A Driox storage tank and vaporizer will be provided with capacity for at least 24 hours of oxygen backup at the rated generation-plant-product automatic flow.

Chapter VI
ECONOMIC CONSIDERATIONS

The economics of oxygen use in the activated-sludge process relative to a conventional air-activated-sludge process derives from the relative process differences discussed in earlier sections of this report. The process and operational advantages notwithstanding, the essence of the economic decision is that sufficient savings in investment and operating costs must be shown within the wastewater-treatment plant as a system to justify the selection of oxygen. Thus, it is necessary to consider such costs as sludge handling and disposal, as well as the direct costs of installing and operating the activated-sludge part of the waste-treatment plant.

DIRECT FACTORS

The direct economic factors governing the economics of oxygen versus air for the activated-sludge process include the following:

Higher mixed-liquor solids under aeration can be maintained when using oxygen as the aeration gas, without occurrence of oxygen mass-transfer limitations. Concentrating the active biomass in a smaller volume reduces concrete tankage requirements, and is a chief reason for expecting reduced costs from such a system. This effect can be extremely important when land is limited and when extensive piling work is necessary.

Higher oxygen-transfer efficiencies are made possible using oxygen as the aeration gas. These efficiencies lower equipment requirements for oxygen dissolution, with an attendant reduction in requirements for auxiliary equipment, such as electrical switchgear.

Power savings generally result from the higher oxygen mass-transfer efficiencies experienced in pure-oxygen processes. The power required to generate oxygen for the biological process added to that required for oxygen dissolution generally is less than that required to provide oxygen to a conventional activated-sludge process with air as the oxygen source.

INDIRECT FACTORS

The economics of oxygen are also governed by indirect considerations, such as sludge handling and disposal and odor control.

The improved settling characteristics of oxygen sludge result in the achievement of a much thicker clarifier-underflow concentration than is achievable with conventional aeration systems at the same overflow rate. This effect allows the maintenance of higher mixed-liquor concentrations, but also provides advantages in sludge handling and disposal, since the waste solids from the secondary clarifier are available in a significantly decreased volume of liquid.

Substantial evidence in many operating programs continues to indicate that less total pounds of dry solids will be produced with an oxygen process than with conventional aeration-activated sludge. This result will also affect the economics of sludge handling and disposal.

The excellent flocculating characteristics of oxygen sludge, which account for improved settling characteristics in a secondary clarifier, also contribute to improved performance in sludge-handling equipment, such as centrifuges and vacuum filters.

Odor control is frequently an important consideration in selection of oxygen for secondary treatment. Since nitrogen is rejected from the gas feed to the process before using the oxygen, and since 90 percent of the oxygen is consumed compared with about 5 percent for conventional air-activated-sludge processes, the total gas volume vented from an oxygen system is normally less than 1 percent of the volume vented from a conventional air process. This gas is vented at a single point rather than from the entire surface area of the tank and, therefore, can be collected for further odor treatment if desirable.

SCOPE OF SUPPLY

The scope of supply of oxygen equipment for use in an activated-sludge process is small relative to the equipment requirements for a wastewater-treatment plant. Union Carbide's scope of supply includes the oxygen-generation plant, the equipment for oxygen dissolution, and the instrumentation and controls to integrate this equipment into the activated-sludge process. Union Carbide does not supply concrete tanks or covers, clarifiers, liquid pumps and controls, or any sludge-handling and disposal equipment, but prefers to work with the consultant to integrate the Union Carbide equipment into the equipment best supplied and constructed under the control of the consultant. Given this method of operation and the economic effects discussed earlier, it is of little or no value to discuss the cost of Union Carbide-supplied equipment only. Rather, it is necessary to consider the overall economic consequences to the waste-treatment facility of a decision to install oxygen for the activated-sludge part of the plant. In practice, this economic comparison is performed by the consultant as an integral part of his process evaluation and selection service to his client. Union Carbide participates by providing economic data covering its own scope of supply for each specific case. With such a procedure the total economics are rarely known to Union Carbide until the overall evaluation-and-selection process is complete and published. A few such evaluations are available and are summarized in the following section.

COMPARATIVE ANALYSES

Middlesex County, N.J.

A 300-day pilot-plant program was conducted prior to process selection of Unox by the Middlesex County Sewerage Authority and the consultant Metcalf & Eddy. The economics were prepared comparing complete-mix, air-activated sludge with oxygen for a 120-mgd plant. Table VI-1 shows the results as published.

Table VI-1.—*Economic evaluation, Middlesex County, N.J.*

Cost component	Unox	Air-activated sludge
	Dollars	
Capital	83,580,000	104,020,000
Operating cost per year	7,390,000	8,290,000

Detroit, Mich.

The city of Detroit and the consultant Hubbell, Roth and Clark determined economics for their initial 300-mgd plant installation. For this portion of their ultimate 1,200-mgd requirements their economic evaluation indicated a 20-percent savings for the aeration-tank portion only. Their evaluation compared a Unox system with a 2.28-hour-detention-time, air-activated-sludge system (see table VI-2).

Table VI-2.—*Economic evaluation, Detroit, Mich.*

Cost component	Unox	Air-activated sludge
	Dollars	
Capital	39,500,000	51,700,000
Operating cost per year	1,599,000	1,911,000

Oakland, Calif.

A pilot-plant program was completed recently at the East Bay Municipal Utility District plant in West Oakland, Calif. The Unox system was selected for the West Oakland plant after meetings with the U.S. Environmental Protection Agency, the State Water Resources Control Board, and the Bay Area Regional Water Quality Control Board. Unox was selected, not only for economic considerations, but because the data indicated that pure oxygen was more reliable and provided a higher margin of safety in meeting Federal and State standards. The system also will serve as a building block for additional systems, if additional water-quality standards are imposed on the San Francisco Bay dischargers in the future. Indicated costs for Unox in comparison with a chemical-treatment and trickling-filter process are given in table VI-3.

Table VI-3.—*Economic evaluation, Oakland, Calif.*

Cost component	Unox	Chemical treatment plus trickling filter
	Dollars	
Capital	47,000,000	56,000,000
Operating cost per year	4,000,000	4,900,000

Euclid, Ohio

One evaluation has been released on a plant substantially smaller than the Detroit and Middlesex jobs. The Euclid, Ohio, design was prepared by Havens and Emerson for a plant size of 22 mgd. The published economics (see table VI-4) indicated a total capital savings of 20 percent for Unox.

Table VI-4.—*Economic evaluation, Euclid, Ohio*

Cost component	Unox	Air-activated sludge
	Dollars	
Capital	10,000,000	12,000,000
Operating cost per year	1,120,000	1,180,000

Union Carbide Cost Projections

Union Carbide has attempted some economic analysis; however, generalization is difficult because of the many different circumstances existing in each specific location. The value of land, piling requirements, and method of sludge disposal, among other factors, always affect the specific case. The published economics in the EPA report[1] covering the initial demonstration of oxygen at Batavia is an attempt at generalization. While the absolute numbers certainly are not applicable for every specific treatment plant, Union Carbide does find that the general conclusions appear valid. In general, the economic attractiveness of oxygen improves as plant size increases, because large-size oxygen generators are more cost effective. At the time of this report, oxygen has been selected at a number of plants in the 4-6-mgd range, but below that size economic factors have not been favorable except in the industrial market, where high-strength wastes are being treated. Union Carbide is currently completing technical and market development work of preengineered plants in the 1-5-mgd range employing pure oxygen. The projected installed costs for these plants appear in table VI-5. Costs as presented include all tankage and equipment, as well as installation.

Preengineered Unox plants can be offered with oxygen supply from LOX or from onsite oxygen generators. The operating costs of these plants are comparable throughout the range, and, therefore, oxygen systems can be expected to compete favorably with air systems in this plant-size range.

Table VI-5.—*Projected installed-plant costs*

Capacity, mgd	Unox	Conventional air
	Dollars	
0.5	130,000	130,000
2.0	320,000-400,000	370,000-390,000
5.0	530,000-700,000	700,000-750,000

REFERENCES

[1] Environmental Protection Agency, Project No. 17050DNW, May 1970.

[2] Environmental Protection Agency, Project No. 17050DNW, Feb. 1972.

[3] *Standard Methods for the Examination of Water and Wastewater*, 13th ed., American Public Health Association, New York, N.Y., 1971.

Appendix A

SPECIFICATIONS FOR FINAL SETTLING TANKS*

1. Overflow rate of maximum day is 1,200 gal/ft^2/day.

2. Solids loading at Middlesex County Sewerage Authority (MCSA) will be 34 lb/ft^2/day of tank area for design flow of 120 mgd with mixed-liquor concentration at 5,500 mg/l. This loading increases to 55 lb/ft^2/day at maximum loading.

3. Sludge-volume index must be looked at carefully. Sludge-volume index is the volume in milliliters occupied by settled mixed liquor containing 1 gram of dry solid. The sludge-volume index for a 2,000-mg/l mixed liquor that settles to 25 percent in 30 minutes is 125; however, the sludge-volume index of an 8,000-mg/l mixed liquor that does not settle at all in 30 minutes is 125. Obviously a good sludge-volume index for conventional activated sludge may be very poor for Unox sludge, which has a mixed-liquor concentration in the final tank influent two to six times greater.

4. Settleability rates are a much better method for comparison. Figure A-1 gives some indication of MCSA Unox-sludge initial settling velocities.

5. Return-sludge concentration varies from 1.5 to 3.0 percent. MCSA is designed for 2.2 percent.

6. Normal return-sludge rate is 33 percent of influent wastewater flow. Maximum rate is 100 percent.

7. Union Carbide has preferred to have the rate of return sludge proportional to the Unox influent. This rate theoretically maintains the same mixed-liquor concentrations in the oxygenation tanks. This theory holds true at the moment the change is made, because the return-sludge concentration has not changed; however, an increase in mixed-liquor flow of the same concentration reduces the period of retention of the liquid and the sludge and increases the overflow rate and solids-loading rate, with the possibility that solids separation will be reduced and the mixed-liquor concentration will decrease. Union Carbide is having second thoughts on keeping the return sludge proportional to the Unox influent.

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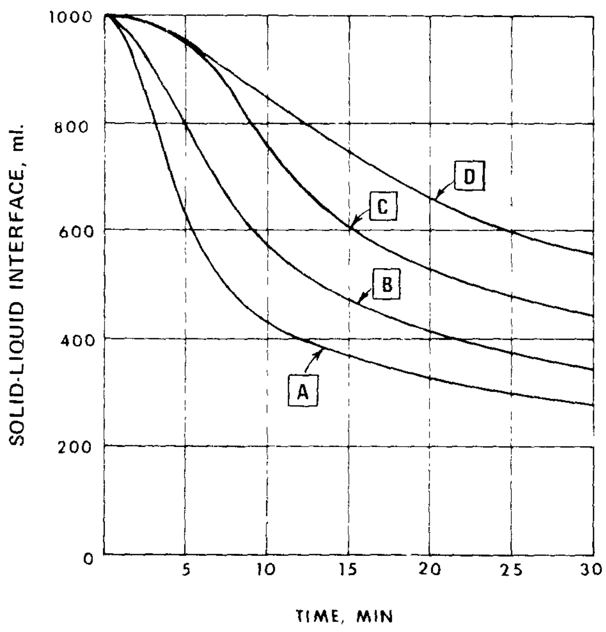
*Prepared by Ariel Thomas, Metcalf & Eddy, Engineers, New York, N.Y.



DATE	CURVE	INITIAL SOLIDS CONCENTRATION, MG/L	INITIAL SETTLING VELOCITY FPH
2/25-26	A	4200	6.4
wk. of 5/16	B	5400	4.9
wk. of 6/6	C	6400	2.9
12/8/70	D	7200	1.6

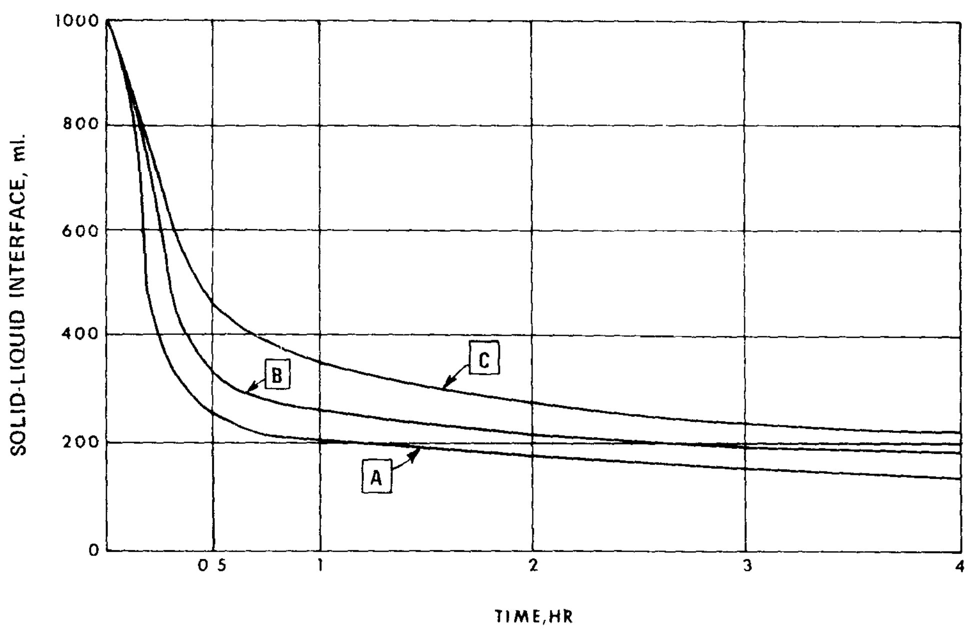


Figure A-1. Typical solids-settleability curves.

Appendix B

SPECIFICATIONS FOR OXYGENATION TANKS*

1. BOD removals are specified approximately 90 percent.

2. Tank volume is based on 160 pounds of BOD_5 per 1,000 cubic feet (average); Unox engineers believe that this base can be increased to 215 pounds or higher.

3. MLSS specifications are 5,500 mg/l.

4. MLVSS specifications are 5,000 mg/l.

5. F/MLVSS ratio is 0.510; Unox believes that this ratio can be much higher.

6. Mixed-liquor DO is targeted at 3-9 mg/l.

7. Purity of applied GOX is as follows: cryogenic, 95 percent minimum; PSA, 90 percent.

8. Oxygen in waste gas is specified at 50 percent.

9. Applied oxygen consumed is 90 percent.

10. Mixing equipment and sparger:

    10.1 Sparger and mixer are on same shaft.

    10.2 Shaft is hollow and carries compressed oxygen-rich gas to sparger.

    10.3 Sparger and mixer turn at a constant speed, which will keep contents of oxygenation tanks mixed.

    10.4 Mixer may be ship-type propeller or pitched-blade turbine.

    10.5 Oxygen compressors for oxygenation tanks are centrifugal, with suction throttling.

    10.6 For Middlesex County Sewerage Authority (MCSA), mixer is 6,000 hp and compressor is 5,100 hp, of which 1,900 is standby. All of the mixer horsepower is connected and in operation at all times. MCSA expects that total power for mixing and dissolution will be less than 0.161 kW-h per pound of oxygen dissolved.

    10.7 Oxygen-compressor suction pipes are subject to condensing and freezing of moisture in the oxygen-gas stream in cold weather.

    10.8 Special lubricants must be used if oxygen comes in contact with lubricant.

    10.9 The mixer shaft rotates in a liquid seal, which is part of shaft-and-mixer-skid assembly.

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*Prepared by Ariel Thomas, Metcalf & Eddy, Engineers, New York, N.Y.

10.10 Spare mixer motor, speed reducer, shaft, propeller, and sparger must be stored onsite.

10.11 Standby compressors must be installed for each oxygenation stage or, sometimes, one for two stages.

11. Normal oxygen pressure under covers of oxygenation tanks is 2 inches of water.

12. Tank covers are designed for 100 pounds of live load and 4 inches of vacuum.

13. Oxygen feed into the first pass is controlled by pressure under the covers in the first pass. The approximate set point is 2 inches.

14. The pressure in the first pass is controlled by the rate of oxygen use and the purity of the gases vented to the atmosphere from the fourth pass. If the oxygen content is more or less than 50 percent, then the vent valve closes or opens, as necessary, to bring purity back to 50 percent. Vent-gas O_2 purity can be varied.

15. DO in each pass is controlled by the rate of discharge of compressed oxygen-rich gas to that pass. The compressors can be controlled automatically or manually using DO meters.

16. Waste gas must be discharged into a stack approximately 15 feet high, so that the waste oxygen will have a chance to mix before it reaches the ground.

17. BOD_5 applied to the oxygenation tanks varies during the day, daily, weekly, monthly, and with growth. The amount of oxygen required to meet the BOD_5 demand varies with the volumetric BOD_5 loading. As the loading increases the amount of oxygen required rises at a decreasing rate (see fig. B-1). Note that, at the design loading of 160 pounds of BOD_5 per 1,000 cubic feet, 1.8 pounds of oxygen are required to remove 1 pound of BOD_5. As the loading increases to 255, the amount of oxygen required to remove 1 pound of BOD_5 drops to 1.3 pounds.

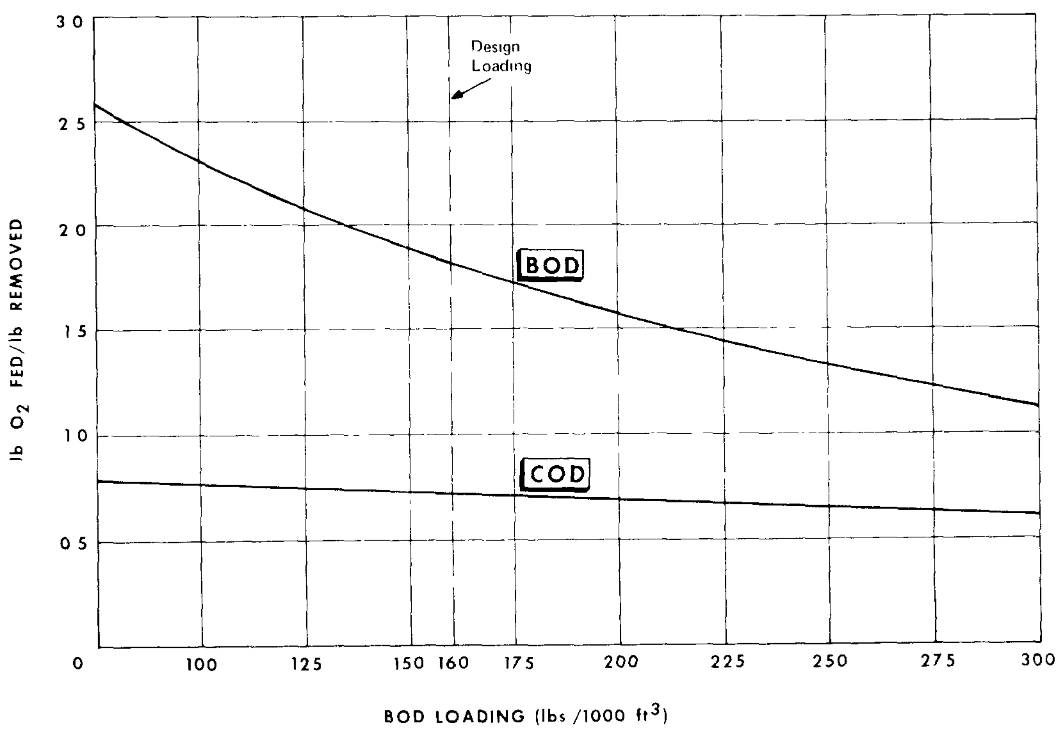

Figure B-1. Oxygen-demand curve.

Recommended Units

Description	Unit	Symbol	Comments	Customary Equivalents
Length	metre	m	*Basic SI unit*	39.37 in.=3.28 ft= 1.09 yd
	kilometre	km		0.62 mi
	millimetre	mm		0.03937 in.
	micrometre	μm.		3.937 X 10^{-3}=10^3A
Area	square metre	m^2		10.764 sq ft = 1.196 sq yd
	square kilometre	km^2		6.384 sq mi = 247 acres
	square millimetre	mm^2		0.00155 sq in.
	hectare	ha	The hectare (10 000 m^2) is a recognized multiple unit and will remain in international use.	2.471 acres
Volume	cubic metre	m^3		35.314 cu ft = 1.3079 cu yd
	litre	l	The litre is now recognized as the special name for the cubic decimetre.	1.057 qt = 0.264 gal = 0.81 X 10^{-4} acre-ft
Mass	kilogram	kg	*Basic SI unit*	2.205 lb
	gram	g		0.035 oz = 15.43 gr
	milligram	mg		0.01543 gr
	tonne or megagram	t Mg	1 tonne = 1 000 kg 1 Mg = 1 000 kg	0.984 ton (long) = 1.1023 ton (short)
Time	second	s	*Basic SI unit*	
	day	d	Neither the day nor the year is an SI unit but both are important.	
	year	year		
Force	newton	N	The newton is that force that produces an acceleration of 1 m/s^2 in a mass of 1 kg.	0.22481 lb (weight) = 7.233 poundals
Moment or torque	newton metre	N-m	The metre is measured perpendicular to the line of action of the force N. Not a joule.	0.7375 ft-lbf
Stress	pascal	Pa		0.02089 lbf/sq ft
	kilopascal	kPa		0.14465 lbf/sq in

Recommended Units

Description	Unit	Symbol	Comments	Customary Equivalents
Velocity linear	metre per second	m/s		3.28 fps
	millimetre per second	mm/s		0.00328 fps
	kilometres per second	km/s		2.230 mph
angular	radians per second	rad/s		
Flow (volumetric)	cubic metre per second	m^3/s	Commonly called the cumec	15,850 gpm = 2.120 cfm
	litre per second	l/s		15.85 gpm
Viscosity	pascal second	Pa-s		0.00672 poundals/sq ft
Pressure	newton per square metre or pascal	N/m^2 Pa		0.000145 lb/sq in
	kilometre per square metre or kilopascal	kN/m^2 kPa		0.145 lb/sq in.
	bar	bar		14.5 b/sq in.
Temperature	Kelvin	K	*Basic SI unit*	$\frac{5F}{9} - 17.77$
	deqree Celsius	C	The Kelvin and Celsius degrees are identical. The use of the Celsius scale is recommended as it is the former centigrade scale.	
Work, energy, quantity of heat	joule	J	1 joule = 1 N-m where metres are measured along the line of action of force N.	2.778 X 10^{-7} kw hr = 3.725 X 10^{-7} hp-hr = 0.73756 ft-lb = 9.48 X 10^{-4} Btu
	kilojoule	kJ		2.778 kw-hr
Power	watt	W	1 watt = 1 J/s	
	kilowatt	kW		
	joule per second	J/s		

Application of Units

Description	Unit	Symbol	Comments	Customary Equivalents
Precipitation, run-off, evaporation	millimetre	mm	For meteorological purposes it may be convenient to measure precipitation in terms of mass/unit area (kg/m^3). 1 mm of rain = 1 kg/m^2	
River flow	cubic metre per second	m^3/s	Commonly called the cumec	35.314 cfs
Flow in pipes, conduits, channels, over weirs, pumping	cubic metre per second	m^3/s		
	litre per second	l/s		15.85 gpm
Discharges or abstractions, yields	cubic metre per day	m^3/d	1 l/s = 86.4 m^3/d	1.83 X 10^{-3} gpm
	cubic metre per year	m^3/year		
Usage of water	litre per person per day	l/person day		0.264 gcpd
Density	kilogram per cubic metre	kg/m^3	The density of water under standard conditions is 1 000 kg/m^3 or 1 000 g/l or 1 g/ml.	0.0624 lb/cu ft

Application of Units

Description	Unit	Symbol	Comments	Customary Equivalents
Concentration	milligram per litre	mg/t		1 ppm
BOD loading	kilogram per cubic metre per day	kg/m^3d		0.0624 lb/cu-ft day
Hydraulic load per unit area; e.g. filtration rates	cubic metre per square metre per day	m^3/m^2d	If this is converted to a velocity, it should be expressed in mm/s (1 mm/s = 86.4 m^3/m^2 day).	3.28 cu ft/sq ft
Hydraulic load per unit volume; e.g., biological filters, lagoons	cubic metre per cubic metre per day	m^3/m^3d		
Air supply	cubic metre or litre of free air per second	m^3/s l/s		
Pipes diameter	millimetre	mm		0.03937 in.
length	metre	m		39.37 in. = 3.28 ft
Optical units	lumen per square metre	$lumen/m^2$		0.092 ft candle/sq ft