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Develop and Demonstrate Fundamental Basis for Selectors to Improve Activated Sludge Settleability

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DEVELOP AND DEMONSTRATE FUNDAMENTAL BASIS FOR SELECTORS TO IMPROVE ACTIVATED SLUDGE SETTLEABILITY

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East Bay Municipal Utility District

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ABSTRACT AND BENEFITS

Abstract:

Although selectors have been widely applied to control filamentous bulking in activated sludge systems, significant variation exists in design and operating practices and the degree of sludge settleability achieved. The goal of this research was to investigate fundamental issues regarding the growth and control of specific filamentous organisms at bench scale, develop an extensive database of selector design and operating data from full-scale facilities, and demonstrate implementation of full-scale, pilot anaerobic selectors at two large wastewater treatment plants. Based on data collected from 44 facilities, this project examines the relationship between various process parameters and settleability control.

This study identifies the most significant process variables affecting settleability control in three distinct plant categories—short-MCRT with anoxic or anaerobic selectors, short-MCRT with aerobic selectors, and long-MCRT—and provides recommended design and operating ranges based on single-variable regression analysis of a large database of full-scale plant data. The project team has incorporated this information into a computerized selector diagnostic tool that may be used to retrieve recommended design and operating ranges from the current study and the literature based on user input.

Benefits:

- Evaluates the role of readily assimilable chemical oxygen demand (raCOD) in the growth and control of *Thiothrix* spp.
- Documents selector performance and operating data from 44 full-scale facilities.
- Evaluates the relationship between various process variables and settleability control.
- Demonstrates implementation of full-scale, pilot anaerobic selectors at two facilities.
- Provides a semi-empirical formula for calculating the "effective" number of selector compartments (N) in a selector zone based on flow conditions and basin geometry when dye study results are not available.
- Ranks selector design and operating parameters based on the influence on settleability for three different plant categories—short-MCRT with anoxic or anaerobic selectors, short-MCRT with aerobic selectors, and long-MCRT.
- Provides recommended design and operating ranges for the most critical process variables in each of the three plant categories.
- Provides a computerized selector diagnostic tool (available on CD-ROM attached to inside of back cover of report) to assist in troubleshooting existing selectors or designing new selectors based on user input and design/operating parameter recommendations from this study and the literature.

Keywords: Selector, filamentous bulking, settleability

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BOD	biochemical oxygen demand
BNR	biological nutrient removal
CMAS	completely mixed activated sludge
COD	chemical oxygen demand
CSTR	continuous-flow stirred tank reactor
DNA	deoxyribose nucleic acid
DO	dissolved oxygen
DSVI	diluted sludge volume index
EBMUD	East Bay Municipal Utility District
EBPR	enhanced biological phosphorus removal
F/M	food-to-microorganism ratio
GAO	glycogen-accumulating organism
HP	horsepower
HRT	hydraulic residence time
ICZ	initial contact zone
LCFA	long-chain fatty acid
MCRT	mean cell residence time
MLSS	mixed liquor suspended solids
mV	millivolts
MWWTP	Main Wastewater Treatment Plant (EBMUD)
OCSD	Orange County Sanitation District
OUR	oxygen uptake rate
PAO	phosphorus-accumulating organism
PHB	poly-β-hydroxybutyrate
RAS	return activated sludge
raCOD	readily assimilable COD
rRNA	ribosomal ribose nucleic acid
saCOD	slowly assimilable COD
sCOD	soluble COD
SBR	sequencing batch reactor
SCFA	short-chain fatty acid
SSV_{30}	30-min settled sludge volume
SVI	sludge volume index
TAG	triglyceride
UCT	University of Cape Town (South Africa)
UOSA	Upper Occoquan Sewage Authority
VIF	variance inflation factor
WAS	waste activated sludge

EXECUTIVE SUMMARY

ES.1 Key Findings

In brief, this study supports the following conclusions:

- ♦ Anoxic selectors do not appear to control filamentous bulking in long-mean cell residence time (MCRT) plants. In fact, the elimination of all anoxic zones may help to control bulking in these plants. Other design/operating parameters, however, were shown to influence activated sludge settleability in long-MCRT plants.
- ♦ Aerobic selectors in short-MCRT plants do control filamentous bulking if they are small enough to produce a biochemical oxygen demand (BOD) concentration gradient in the aeration basins.
- ♦ Anoxic and anaerobic selectors do control filamentous bulking in short-MCRT plants if the selector volume is large enough and/or the selector mixed liquor suspended solids concentration is high enough. These selector systems do not appear to benefit from a BOD concentration gradient as the aerobic selectors in short-MCRT plants do. Although anaerobic/anoxic selector compartmentalization in these plants appears to improve settleability, this is presumably because of reduced selector short-circuiting.

To make the study findings more readily available to practitioners, the project team prepared a computerized selector diagnostic tool, which is included on a CD-ROM attached to the inside back cover of this report. Documentation for this software application is provided in Appendix F, which explains the simple steps to using the selector diagnostic tool software. This study's findings can be used immediately through this software to help an operator troubleshoot a poorly-performing selector or help an engineer design a better-performing selector.

If the practitioner is interested in how the selector diagnostic tool's guidelines were derived, Chapter 4.0 can be referenced. If the practitioner is interested in an actual demonstration of these guidelines, Chapter 5.0 can be referenced. Chapter 6.0 provides a more detailed summary of the study's findings and conclusions, Chapter 2.0 provides a selector literature review, and Chapter 3.0 provides laboratory study results demonstrating the role of readily assimilable chemical oxygen demand (raCOD) in selector performance. Refer to the discussion on raCOD in Chapter 1.0, Page 1-3.

As shown in Chapter 5.0, a selector system does not need to comply with all the design/operating parameter ranges listed in the selector diagnostic tool's results tables to control filamentous bulking. The East Bay Municipal Utility District (EBMUD) selector worked well and only complied with three parameters. Since the parameters are listed in order of their influence on diluted sludge volume index (DSVI), those listed first in the diagnostic tool's results table are those that the selector operator or designer should be primarily concerned with.

A more detailed summary of this study's findings is presented in the next section.

ES.2 Project Objectives

Selector processes have been widely applied to control filamentous bulking in activated sludge systems for more than thirty years. Still, the literature does not provide a consistent set of selector process design or operating guidelines. Variation in the degree of sludge settleability control achieved, represented by the sludge volume index (SVI), for similar process designs has dictated that selectors be designed on an empirical basis, relying heavily on design concepts and demonstrated performance at facilities with similar wastewater characteristics and process configurations.

The primary objectives of this research were to:

- Investigate the mechanisms limiting the ability of a selector to control the growth of specific filamentous organisms known to cause bulking;
- Establish a project database of selector design and performance from a large pool of full-scale facilities from across the U.S.;
- Identify selector design and performance relationships for each of the three main selector categories (aerobic, anoxic, and anaerobic) based on the project database information collected; and
- Demonstrate the implementation of a full-scale anaerobic selector at two wastewater treatment facilities and identify associated selector design and performance issues.

ES.3 Project Approach

Based on the project objectives, this study was divided into five main project tasks:

1. Literature Review
2. Laboratory Investigation
3. Initial Plant Screening Survey
4. Detailed Plant Investigations
5. Full-Scale Demonstration Projects

Dr. H. David Stensel (University of Washington, Seattle) conducted a literature search and review of selector-related topics, including filament type and occurrence in activated sludge systems, kinetic and metabolic substrate removal mechanisms, available full-scale selector design and performance data, and current research efforts related to the control of specific filamentous organisms. The goal of the literature review was to highlight key issues for application to subsequent project tasks.

The literature review illustrated that selector design approaches are focused on the removal of raCOD, while some selector designs often fail if process conditions favor the growth of filamentous organisms that thrive on slowly assimilable chemical oxygen demand (saCOD). In order to further examine this issue, under Dr. Stensel's direction, Gang Xin conducted a bench-scale, laboratory experiment to investigate the ability of an aerobic selector to control two specific filamentous organism types—one that prefers raCOD (Type 021N, *Thiothrix*) and one that thrives on saCOD (*Microthrix parvicella*, Type 0092).

This study focused primarily on collecting and analyzing selector design and operating data from full-scale facilities from across the U.S. As an initial step, a screening survey form, designed to be completed in a relatively short time period, was distributed to a large number of wastewater facilities from across the country. The initial screening survey was used to establish plant contacts at a large pool of facilities equipped with selectors of various types, collect basic selector design (type, configuration) and performance data (SVI), and identify candidate facilities interested in participating further in the study.

Following completion of the initial screening survey, many of the facilities were carried forward as part of a detailed plant investigation task. During this phase, plants were asked to provide more detailed information regarding both plant and selector design and operation, including one year of plant operating and selector performance data. Based on the activated sludge operating data provided, a number of important design parameters were calculated in order to compare selector design and performance between facilities and selector types. For the purposes of this study, the diluted SVI (DSVI) was selected as the most accurate representation of sludge settleability at these facilities because of the dependency of the SVI test on mixed liquor suspended solids (MLSS) concentration. Single variable regression analyses were conducted to evaluate the relationship between a wide array of process variables and the DSVI achieved (dependent variable). The results were compared to literature design and operating guidelines whenever possible.

Since selectors are often installed as retrofits to existing facilities rather than included in original plant designs, this study included the performance demonstration of full-scale anaerobic selectors installed at two wastewater treatment facilities—the EBMUD Main Wastewater Treatment Plant (MWWTP) in Oakland, Calif., and the Orange County Sanitation District (OCSD) Plant No. 1 in Fountain Valley, Calif. The goal of this work was to provide municipalities with key information necessary for successful selector implementation at their facilities by highlighting process considerations and issues.

ES.4 Literature Review

The following is a summary of the main literature review findings:

- A combined survey of 270 U.S. facilities (Jenkins et al. 2004) indicated that the most common filament types were (in order of frequency of occurrence) Type 1701, Type 021N, and *Thiothrix*, while a survey of 33 long-MCRT, biological nutrient removal (BNR) plants in South Africa (Blackbeard et al., 1987) found Type 0092, Type 0675, Type 0041, *M. parvicella*, and Type 0914 to be most common.
- Aerobic selectors promote kinetic conditions favoring preferential substrate uptake and sequestering by floc-formers over filamentous organisms. Anoxic selectors create a metabolic advantage for floc-formers, since most filamentous organisms are unable to denitrify (use nitrate as an electron acceptor) or have relatively low denitrification rates. Similarly, the feed-starve cycle employed in anaerobic selectors allows metabolic selection of floc-forming, phosphorus-accumulating organisms (PAOs) or glycogen-accumulating organisms (GAOs) over filamentous organisms.
- Selectors will be most successful in situations where the target filaments use raCOD as substrates. Selectors may fail if the target filament uses saCOD or sulfide or is favored by low pH or nutrient deficient conditions.
- Some filament types, such as *M. parvicella*, use saCOD [long-chain fatty acids (LCFAs)] for substrate and will proliferate in selector systems under the following conditions: zero or low dissolved oxygen (DO), long MCRT, and low temperature.
- A review of pilot- and full-scale selector design and operating data showed that a wide range of SVI control was achieved, with some installations reporting no significant improvement in bulking control. Single-stage designs are used for anoxic and anaerobic selectors, while most aerobic selectors include a staged design.

The following is a summary of general selector design guidelines found in the literature:

- ♦ Substrate Removal – The soluble COD (sCOD) leaving the selector should be <60 mg/L (Shao and Jenkins, 1989) and the raCOD should be virtually absent. The selector should remove 80% of the removable COD (Chudoba and Wanner, 1987).
- ♦ Selector Staging and Configuration – All three selector types (aerobic, anoxic, anaerobic) should be designed with at least three stages, sized at 25%, 25%, and 50% of the total selector volume, respectively (Jenkins et al., 2004). A staged-selector arrangement is necessary to create a food-to-microorganism (F/M) gradient (Albertson, 2005).
- ♦ Aerobic Selectors – Aerobic selectors should be staged to provide proper kinetic conditions favoring rapid substrate uptake and storage by floc-formers over filaments. Jenkins et al. (2004) recommended a three-stage design, sized at 25%, 25%, and 50% of the total selector volume with first stage and total F/M loadings of 12 kg COD/(kg MLSS·d) and 3 kg COD/(kg MLSS·d), respectively.
- ♦ Anoxic Selectors – In single-stage arrangements, the selector F/M should be ≤1 kg BOD_5/(kg MLSS·d) for temperatures ≤18ºC and ≤1.5 kg BOD_5/(kg MLSS·d) for temperatures >18ºC, while the anoxic MCRT should be at 1-2 d (Marten and Daigger, 1997). Grady et al. (1999) recommended an anoxic MCRT of 1.0 d at temperatures >20ºC and 1.5 d at temperatures <17ºC. Jenkins et al. (2004) recommended a three-stage design, sized at 25%, 25%, and 50% of the total selector volume with first-stage and total F/M loadings of 6 kg COD/(kg MLSS·d) and 1.5 kg COD/(kg MLSS·d), respectively.
- ♦ Anaerobic Selectors – A three-stage selector with a total selector hydraulic residence time (HRT) of 0.75–2.0 h is recommended (Jenkins et al., 2004).

ES.5 Laboratory Investigation

Four 3-L bench-scale, completely mixed activated sludge (CMAS) units (R1, R2, R3, and R4) were initially seeded with activated sludge containing both *Thiothrix* spp. (raCOD filament) and *M. parvicella* (saCOD filament). The reactors were fed a synthetic wastewater high in Tween 80 (water soluble oleic acid ester of sorbitol) and acetate to promote the growth of both raCOD and saCOD filament types. After an initial startup period, the following changes were made: 1) a three-stage aerobic selector was added to R1 (25%, 25%, and 50% of total selector volume), 2) the raCOD constitutents were removed from the feed to R2, and 3) a four-stage aerobic selector was added to R4 (12.5%, 12.5%, 25%, and 50% of total selector volume). No changes were made to R3, which served as the control. Oxygen uptake rate (OUR) batch tests were conducted periodically by adding either acetate (raCOD) or Tween 80 (saCOD) to mixed liquor samples from each reactor. The reactor operating conditions are summarized in Table ES-1.

Table ES-1. Summary of Bench-Scale Reactor Operating Conditions.

Reactor No.	Description	Operating Conditions (all reactors)			
		Wastewater Feed	MCRT(d)	Temp. (ºC)	Air Feed
1	Three-stage aerobic selector	Synthetic, high in LCFAs (oleic acid) and raCOD (acetate)	20	12–15	Intermittent, DO between 0–2 mg/L
2	raCOD removal from feed				
3	Single-stage CSTR				
4	Four-stage aerobic selector				

The DSVI variation over time in each of the four bench-scale units is shown in Figure ES-1. The results suggest that adding a three-stage and four-stage aerobic selector to R1 and R4, respectively, had a similar effect on DSVI reduction as removing raCOD from the feed to R2. The systems equipped with selectors, however, actually achieved slightly improved DSVI values, suggesting that aerobic selectors may do more to control bulking than just remove raCOD. Severe bulking occurred in the control reactor with *Thiothrix* spp. as the dominant filament type. Conditions favoring the growth of *M. parvicella* could not be maintained in any of the reactors.

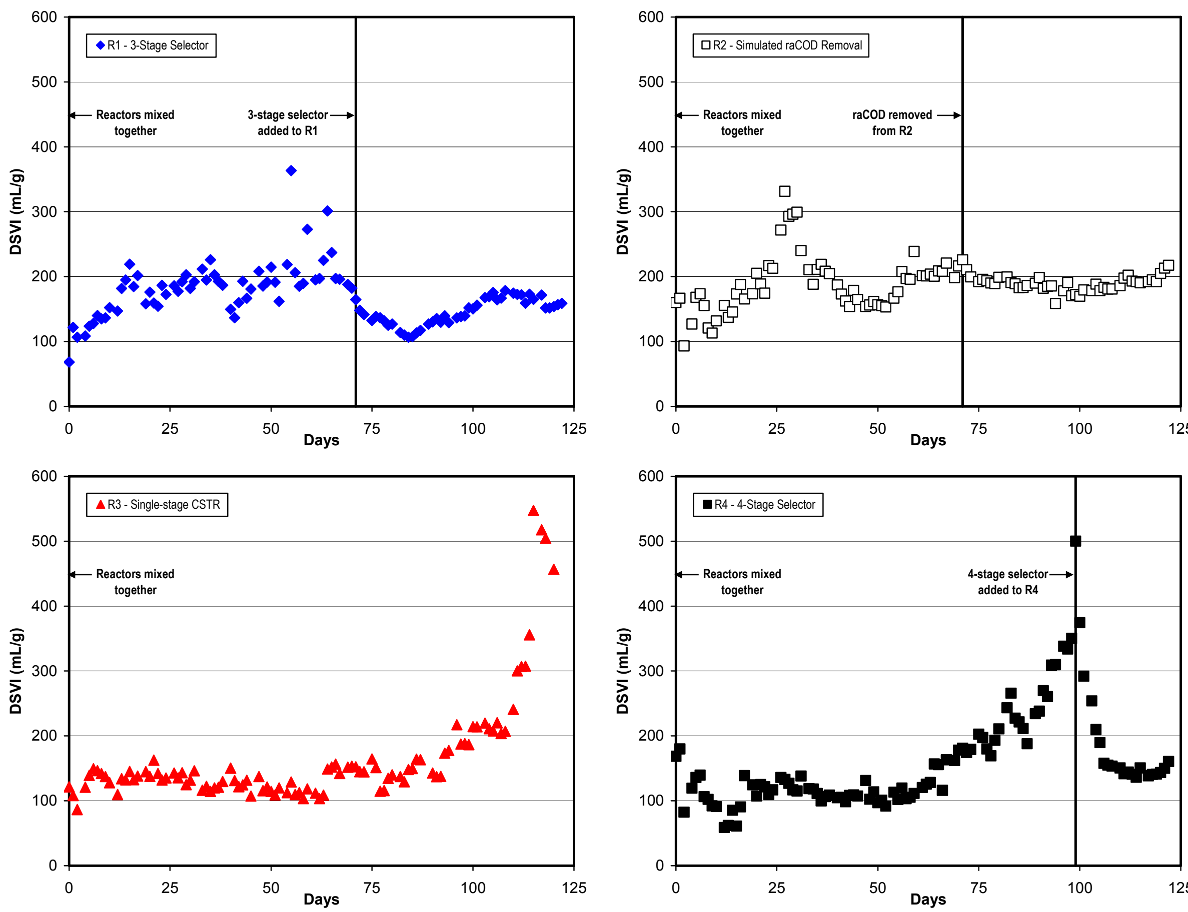

Figure ES-1. Dilute Sludge Volume Index in Four Bench-scale Reactor Systems.

OUR and acetate uptake rates were dramatically reduced in R2 following raCOD removal from the wastewater feed and were significantly less (2-6 times lower for OUR, 3-7 times lower for acetate) than the other reactors. This suggests that the R2 feed without raCOD did not support raCOD floc-forming bacteria growth and that the presence of these bacteria may enhance floc structure and settleability. Acetate uptake rates were 6–10 times higher than the Tween 80 uptake rates,which suggests that Tween 80 (and possibly all LCFAs) may not be adequately removed in a selector and could leak into the main aeration zone at sufficient levels to support filamentous bulking. Similar DSVI control was achieved in both the three- and four-stage aerobic selector systems, while sCOD profiles indicated that most of the removal occurred in the first stage.

ES.6 Initial Plant Screening Survey

The initial screening survey included 125 U.S. wastewater treatment plants. Of these facilities, 85 had selectors (aerobic, anoxic, or anaerobic), but only 46 had improved settleability following selector installation, as shown in Figure ES-2.

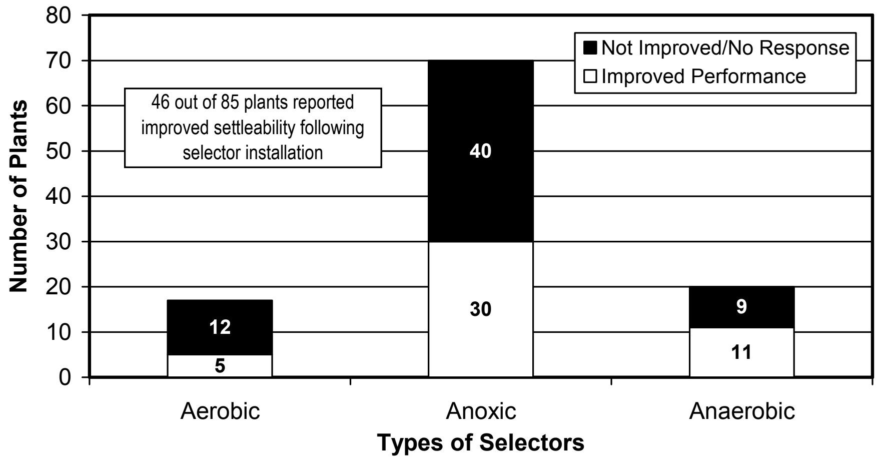

Figure ES-2. Initial Screening Survey Results – Selector Type and Effectiveness.

The initial screening survey form requested the following basic plant information:

- Plant flow rate
- MCRT
- Nutrient removal requirements
- Aeration basin configuration
- Type of selector
- Bulking frequency
- SVI control achieved following selector installation

Given the significant amount of additional plant data to be requested and assuming a moderate response rate, the project team decided to carry forward all 85 facilities reporting selector installations to the detailed plant investigation phase.

ES.7 Detailed Plant Investigations

Table ES-2 summarizes the information requested from each of the 85 facilities included in the detailed plant investigation. In addition to collecting general plant and process configuration information, each facility was asked to provide approximately one year of selector operating and performance data in spreadsheet format. The extensive data collection effort required numerous follow-up data requests and discussions with plant contacts to verify the information provided and to answer plant-specific questions. A number of important selector design and operating parameters were calculated based on the information provided by each plant, as summarized in Table ES-3.

Most facilities reported sludge settleability performance on an SVI basis. Given the dependence of the SVI test result on mixed liquor concentration, as reported by Dick and Vesilind (1969), reported SVI values were converted to DSVIs by applying a correction developed by Merkel (1971). Lee et al. (1983) reported that the DSVI test yielded the best correlation with total extended filament length relative to other techniques for estimating sludge settleability.

Table ES-2. Summary of Detailed Plant Investigation Data Requested.

Category	Description
General Information	• Facility name, location, contact • Average, peak flow rate • Industrial contribution, major contributors • Annual wastewater temperature range • Nutrient removal requirements and processes
Selector Configuration	• Selector type (aerobic, anoxic, anaerobic) • Number and volume of selector stages • Mixing type (hydraulic, mechanical, air) • Available process design criteria, technical reports
Aeration Basin Configuration	• Number and volume of aeration stages and basins • Type of aeration system • Internal recycle streams • Approximate DO profiles • Location of RAS feed points
Additional Plant Information	• Process schematic • Secondary process operation and maintenance (O&M) manuals • Secondary influent sulfide levels • Oxygen uptake rate data • Soluble BOD or COD exiting the selector zone
Plant Operating Data (One Year)	• Secondary influent – flow, BOD, sBOD, COD, sCOD, TKN, P • Number of aeration basins in-service • WAS, RAS flow and concentration • MLSS, MLVSS • System (excluding clarifier solids), aerated MCRT • F/M • DO • Influent or effluent pH • SVI or DSVI • Filament type and abundance • RAS chlorination periods

Table ES-3. Summary of Detailed Plant Investigation Process Data Calculations.

Parameter	Comments
Selector MCRT (d)	Calculation based on mass of mixed liquor in selector zone only
Contact (or floc) loading (kg BOD_5/kg MLSS)	Ratio of influent BOD mass to solids mass in initial contact zone (ICZ)
Selector ICZ F/M loading [kg BOD5/(kg MLSS·d)]	F/M calculation based on mass of mixed liquor in selector ICZ only
Selector HRT (h)	HRT calculation based on volume of selector zone only
90^{th} Percentile SVI (mL/g)	
90^{th} Percentile Merkel DSVI (mL/g)	SVI data converted to DSVI using Merkel equation
Fraction of SVIs greater than 150 mL/g (%)	Represents percent of time SVIs exceed typical control limit

Given the large amount of information requested from each facility, many facilities were not able to provide key information, such as filament type and abundance, SVI, or essential secondary process operating data. Despite this limitation, the study was successful in collecting and verifying data from 44 of the 85 original plants for a total of 48 data sets (four facilities included two data sets representing distinct operating modes). The facility size and selector type distribution is presented in Figure ES-3. A tabular summary of all data collected is included in Table 4-5 in the main report.

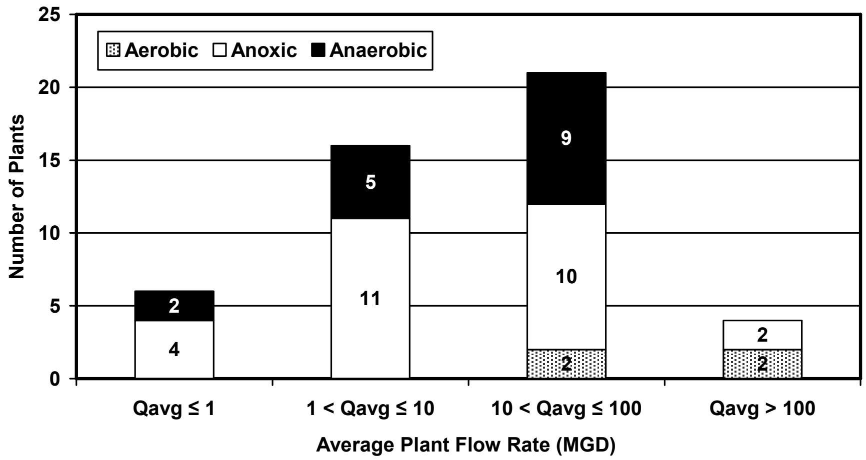

Figure ES-3. Facility Size, Selector Type Distribution.

Average values for a number of selector process design parameters were plotted against both 90th percentile SVI and DSVI results (including the Merkel correction, as necessary). Figure ES-4 is a plot of the ICZ F/M, selector F/M, selector MCRT, system MCRT (excluding clarifier solids), total selector HRT, and number of selector stages versus 90th percentile DSVI. For the purposes of this study, a 90th percentile DSVI value of 150 mL/g was selected as the typical upper limit for well-settling sludge.

The plots in Figure ES-4 clearly indicate that the anoxic selectors achieved greater bulking control relative to the anaerobic selectors. Nearly all of the anoxic selector facilities (23 of 27) had 90th percentile DSVIs <150 mL/g, while nearly all of the anaerobic selector plants (12 of 14) exceeded this limit. Two of five aerobic selector plants also exceeded 150 mL/g. Most anoxic selectors, however, were installed in long-MCRT plants, while all anaerobic selectors were installed in short-MCRT plants (see Figure ES-4). Therefore, the lower DSVI in plants with anoxic selectors may be because of the lower DSVI produced by long-MCRT filamentous bacteria (Wanner, 1994), rather than selector type.

No clear relationships were observed between settleability control and selector ICZ F/M, selector F/M, selector MCRT, system MCRT (excluding clarifier solids), or total selector HRT. In fact, a wide range of DSVIs was observed across a broad range of F/M loading rates, MCRTs, and selector HRTs. Selector staging was not observed to have a significant impact on bulking control in the anoxic selector systems. All eight single-stage anoxic selectors yielded DSVIs <150 mL/g, while four of 18 multi-stage anoxic selectors exceeded this limit. Selector staging was also not observed to have a significant impact on settleability in anaerobic selector systems, since six of seven plants yielded DSVIs >150 mL/g in both the single- and multi-stage categories.