United States
Environmental Protection
Agency

Municipal Environmental Research
Laboratory
Cincinnati OH 45268

EPA-600/2-84-106
June 1984

Research and Development

Design Information on Rotating Biological Contactors

EPA-600/2-84-106
June 1984

DESIGN INFORMATION ON ROTATING BIOLOGICAL CONTACTORS

by

Richard C. Brenner*
James A. Heidman
Edward J. Opatken
Albert C. Petrasek, Jr.

Wastewater Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

*Project Officer

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

DISCLAIMER

This report has been subjected to the Agency's peer and administrative review procedures and approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. The complexity of our environment and the interplay of its components require a concentrated and integrated attack on pollution problems.

Research and development is the necessary first step in problem solution and involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to 1) prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, 2) preserve and treat public drinking water supplies, and 3) minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of the Laboratory's research program and provides a vital communications link between the researcher, the design engineer, and the user community.

This inhouse project was undertaken to evaluate and summarize within one document relevant design information pertaining to the rotating biological contactor (RBC) process. The information presented herein is intended to supplement, not replace, commonly-used RBC design tools such as manufacturers design manuals and catalogs and design procedures published in the technical literature. Factors affecting process selection and design, equipment performance and reliability, and power consumption have been addressed. It is believed this document will be of considerable interest to regulatory and municipal officials, design engineers, and plant operating personnel.

Information was originally presented on the equipment and design practices of six U.S. RBC manufacturers. One manufacturer, referred to hereinafter as Manufacturer X, has recently stopped marketing RBC units. Descriptions of Manufacturer X's equipment have subsequently been removed from this document, but published references to and discussions of its previous design methods have been retained where appropriate.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

The relatively rapid introduction of rotating biological contactors (RBC's) into the United States for municipal wastewater treatment has resulted in the widespread application of a technology with which many design engineers are not intimately familiar. Of necessity, many RBC designs initially were based solely on proprietary-generated empirical design methodology. More recently, as interest in the process has increased, more complex, deterministic design approaches have begun to appear in the technical literature. The purpose of this document is to review and assess existing RBC design procedures and provide more in-depth design information on critical features of the RBC process and key parameters affecting its operation and performance than is typically available to the design engineering community.

The information contained in this document is intended to supplement and qualify that available from RBC manufacturers and in the published literature. Topics addressed include process and design considerations for carbonaceous removal, nitrification, and denitrification; equipment reliability and service life; power requirements for air and mechanical drive RBC units; and general system design considerations involving structural, hydraulic, and operational flexibility. A major priority in the preparation of the document was given to emphasizing practical, usable design information as well as important theoretical concepts.

Office and/or manufacturing facilities of most of the current U.S. proprietors of RBC equipment were visited during the course of preparing this document. Extensive discussions were held with all the manufacturers. The majority of the data used in evaluating the RBC process were obtained from the technical literature, various conference proceedings, and the files of the manufacturers. Field studies were conducted in the greater Cincinnati area to supplement existing power and air flow data for mechanically and air driven RBC's, respectively.

This report was prepared in fulfillment of inhouse Task No. C00/38/E01/B15b of Decision Unit B-113, Program Element CAZB1B. Rigorous literature review, data evaluation, and technical writing were carried out from September 1, 1981, to October 4, 1982. The year-and-a-half since then have been devoted to internal discussions and negotiations within the Agency on several issues addressed in the document, generation of more reliable RBC mechanical drive power data than were available in late 1982, and revisions and additions to the document stimulated by extramural reviews. Final work was completed on April 9, 1984.

CONTENTS

CONTENTS (continued)

CONTENTS (continued)

CONTENTS (continued)

CONTENTS (continued)

FIGURES

FIGURES (continued)

FIGURES (continued)

FIGURES (continued)

TABLES

TABLES (continued)

ACKNOWLEDGEMENTS

The four authors of this document were assisted in their efforts by a diversified, six-member peer review panel that met twice in Cincinnati for 2 days each time. The purpose of the first meeting was to review and modify as needed the initial approach and topic selections of the authors; an in-depth critique of the first draft of the document was conducted at the second meeting. A list of the panel members is given below.

For a technology as new as RBC's and considering the range of topics considered, a number of differing opinions was anticipated and encountered among the authors and peer panel reviewers concerning specific recommendations such as allowable organic and nitrogen loadings, the number of stages required for a given level of treatment, air flow requirements for air driven units, etc. Nonetheless, this document does represent a consensus of opinion of the authors and reviewers on many, but certainly not all, of the topics that were addressed.

Two consultants, Mark D. Bowman and John T. Gaunt of Purdue University, were retained to perform structural analyses related to RBC shaft fatigue design. This material is presented in the latter part of Section 3. In addition, Meyer I. Landsberg, a self-employed consultant from St. Louis Park, Minnesota, was retained to evaluate RBC polyethylene media properties. Excerpts from his report are also presented in Section 3.

The invaluable assistance of Walter T. Schuk of MERL, EPA, Cincinnati in conducting field air flow and power measurements on air and mechanical drive RBC units, respectively, and constructing and calibrating an accurate air flow measurement device is greatly appreciated. The initial leadership of Jeremiah J. McCarthy, formerly of MERL and now with the U.S. Army 10th Medical Laboratory, in forming the document team and establishing guidelines for carrying out the project is gratefully acknowledged. Sincere appreciation is also extended to ASCE's Task Committee on Rotating Biological Contactors, Water Pollution Management Committee, Environmental Engineering Division, for their thorough review comments.

Peer Review Panel

1. Dale A. DeCarlo, Burgess and Niple, Ltd., Columbus, Ohio
2. Donald F. Kincannon, Oklahoma State University, Stillwater, Oklahoma
3. F. Michael Saunders, Georgia Institute of Technology, Atlanta, Georgia
4. O. Karl Scheible, HydroQual, Inc., Mahwah, New Jersey
5. Ed D. Smith, U.S. Army Construction Engineering Research Laboratory, Champaign, Illinois
6. Richard A. Sullivan, Autotrol Corporation, Milwaukee, Wisconsin

METRIC CONVERSIONS

Customary Unit				Metric Unit
cfm	x	4.719×10^{-4}	=	m^3/sec
cu ft	x	2.832×10^{-2}	=	m^3
^oF		$0.556(^oF - 32)$	=	^oC
fpm	x	5.08×10^{-3}	=	m/sec
ft	x	0.3048	=	m
gpd/sq ft	x	4.074×10^{-2}	=	$m^3/day/m^2$
gpm	x	6.308×10^{-5}	=	m^3/sec
gpm	x	6.308×10^{-2}	=	l/sec
hp	x	0.7457	=	kW
hp/100,000 sq ft	x	8.027×10^{-5}	=	kW/m^2
in.	x	25.4	=	mm
in.	x	2.54×10^4	=	µm
ksi	x	7.031×10^5	=	kgf/m^2
lb/cu ft	x	16.02	=	kg/m^3
lb/day/1000 sq ft	x	4.883×10^{-3}	=	$kg/day/m^2$
mgd	x	3.785×10^3	=	m^3/day
mgd	x	4.381×10^{-2}	=	m^3/sec
psi	x	7.031×10^2	=	kgf/m^2
sq ft	x	9.29×10^{-2}	=	m^2
ton (short)	x	9.072×10^2	=	kg

SECTION 1

INTRODUCTION

1.1 Purpose

The primary purpose of this design information document is to provide design information for rotating biological contactor (RBC) treatment of municipal wastewater. Many aspects of this document are equally applicable to industrial wastewater treatment. This document is intended to supplement commonly accepted RBC design methodology, such as manufacturers design manuals, by providing appropriate qualifiers and/or information not readily available to the design community. Important design parameters and relationships (or lack of them) are discussed in order to promote a more rational RBC design approach. Topics addressed include process and design considerations for carbonaceous removal, nitrification, and denitrification; equipment reliability and service life; power requirements for air and mechanically driven units; and general system design considerations involving structural and hydraulic flexibility. Practical, usable design information has been emphasized as well as theoretical concepts. Hopefully, the information in this document will provide the design engineer with a more in-depth perspective on key RBC design considerations than is normally available in existing manuals and reports.

1.2 Brief History of RBC's

The first commercial RBC system was installed in West Germany in 1960. These first RBC units were constructed with flat, 0.5-in. thick, 6.5- to 10-ft diameter, expanded polystyrene sheets. The process became popular in West Germany for small installations.

The J. Conrad Stengelin Company of West Germany licensed the RBC process to the Allis-Chalmers Corporation for manufacturing and sales in the United States. The business was subsequently sold to the Autotrol Corporation* in 1970. Marketing efforts met with limited commercial success until the development of

---

*Autotrol Corporation is referred to throughout this document. On September 17, 1982, Envirex Inc., a subsidiary of Rexnord Inc., acquired certain assets of and manufacturing and future worldwide marketing rights to Autotrol's line of RBC products.

thin, corrugated, high density polyethylene media by Autotrol in 1972. This development increased the available surface area per unit shaft length by 70 to 150 percent, thereby increasing the cost effectiveness of the process in comparison with other economically-feasible secondary treatment alternatives. Polyethylene or plastic media RBC systems are currently offered by a number of proprietors.

At the time of this writing (September 1982), over 550 RBC plants were treating municipal wastewater in the United States (1)(2)(3)(4)(5)(6). The process is used worldwide for both municipal and industrial wastewater treatment. Approximately 70 percent of the RBC systems operating in the United States and Canada are designed for organic carbon removal only, 25 percent for combined organic removal and nitrification, and 5 percent for nitrification of secondary effluent (7). RBC systems have also been designed for upgrading trickling filter plants and for denitrification with methanol addition (with completely submerged media). Approximately 25 percent of the existing RBC municipal facilities in the United States are package plants (8). The largest municipal RBC facility is the 54-mgd system at Alexandria, Virginia. In-depth historical reviews of RBC development are available (9)(10).

RBC media are rotated slowly (1 to 2 rpm) in a wastewater bath, with about 40 percent submerged at any given time. Media rotation is most commonly accomplished by mechanical drives, although air driven units are being employed at some recently completed installations. Typical mechanical and air drive systems with individually covered RBC stages are shown in Figures 1-1 and 1-2, respectively.

A distinguishing characteristic of partially-submerged, rotating plastic media is the alternating exposure of the attached biofilm to air and wastewater. This characteristic, though attractive to many designers, is what makes its rational analysis difficult. Microorganisms respond to the environment surrounding them, and, in the RBC, that environment is continually changing. The requirement for movement of organics and nutrients from the liquid phase into the biofilm and oxygen from the atmosphere into the liquid film, biofilm, and bulk liquid makes it necessary to consider physical mass transfer as well as microbial reaction rates when rationally analyzing RBC performance. By and large, the design community has relied on the various RBC manufacturers to provide the biological design procedures necessary to determine appropriate sizing and staging of RBC systems. These procedures have been and continue to be modified as more process performance information becomes available. As interest in and experience with RBC systems has grown, the related technical literature has also expanded providing alternative design methods and/or approaches to those advocated by the equipment manufacturers.

Problems with the mechanical reliability of RBC systems have been encountered. Premature shaft failures, stub end failures, and media separation/degradation have all been experienced in some installations. Each manufacturer takes a

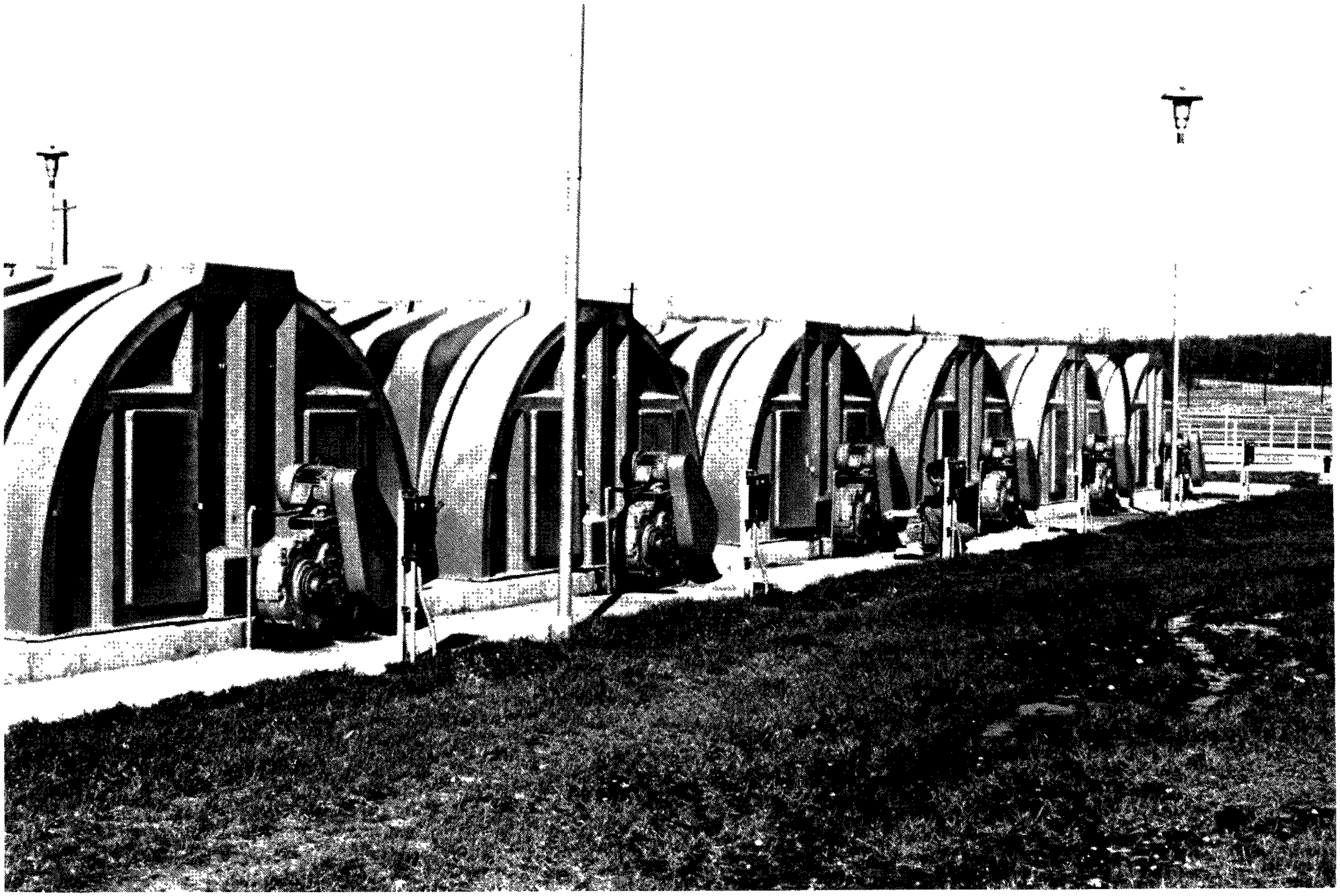


Figure 1-1. Photograph of Clow mechanical drive RBC system at Upper Mill Creek Wastewater Treatment Plant, Butler County, Ohio.

Figure 1-2. Photograph of Autotrol air drive RBC system at Lower East Fork — Little Miami River Regional Wastewater Treatment Facility, Clermont County, Ohio.

somewhat different approach to media configuration; media fabrication, attachment and support; and shaft design, and, as expected, there are differing opinions as to the suitability of alternative equipment. Considerable proprietary effort has been expended in assessing and correcting the equipment deficiencies that have surfaced since the technology's introduction to North America. Since RBC equipment designs are frequently updated, manufacturers' brochures and other information need to be reviewed carefully to assess whether they are current.

1.3 References

1. Personal communication from R. A. Sullivan, Autotrol Corporation, Milwaukee, Wisconsin, to E. J. Opatken, USEPA, Cincinnati, Ohio, September 30, 1982.

2. Personal communication from S. Banerjee, Clow Corporation, Florence, Kentucky, to E. J. Opatken, USEPA, Cincinnati, Ohio, September 29, 1982.

3. Personal communication from R. W. Hankes, Crane Company, Cochrane Environmental Systems, King of Prussia, Pennsylvania, to E. J. Opatken, USEPA, Cincinnati, Ohio,

4. Personal communication from G. Ornstein, Lyco Division of Remsco Associates, Marlboro, New Jersey, to E. J. Opatken, USEPA, Cincinnati, Ohio, September 30, 1982.

5. Personal communication from representative of Manufacturer X to E. J. Opatken, USEPA, Cincinnati, Ohio, September 29, 1982.

6. Personal communication from G. W. Davis, Walker Process Corporation, Aurora, Illinois, to E. J. Opatken, USEPA, Cincinnati, Ohio, September 30, 1982.

7. Hynek, R. J. and H. Iemura. Nitrogen and Phosphorus Removal with Rotating Contactors. *In:* Proceedings of the 1st National Symposium/Workshop on Rotating Biological Contactor Technology, Vol. I, EPA-600/9-80-046a, NTIS PB81-124539, June. pp. 295-314.

8. Chesner, W. H. and J. Iannone. Review of Current RBC Performance and Design Procedures. Report prepared for USEPA, Municipal Environmental Research Laboratory, Cincinnati, Ohio, under Contract No. 68-02-2775 by Roy F. Weston, Inc., (Publication pending).

9. Antonie, R. L. Fixed Biological Surfaces - Wastewater Treatment: The Rotating Biological Contactor. CRC Press, Cleveland, Ohio, 1976.

10. Grieves, C. Dynamic and Steady State Models for the Rotating Biological Disc Reactor. Ph.D. Thesis, Clemson University, Clemson, South Carolina, 1972.

SECTION 2

PROCESS CONSIDERATIONS

2.1 Introduction

Procedures for predicting organic removal, nitrification, and denitrification relationships occurring in the RBC process continue to evolve as additional information becomes available. Relationships that were recommended a few years ago have subsequently been modified or replaced with alternative methodologies. Reported experimental pilot and field data exhibit sufficient variation such that support for conflicting design approaches can usually be found. The present state-of-the-art is such that no single best design procedure or set of relationships is universally applicable.

2.2 Wastewater Carbonaceous Characteristics

The biodegradable materials in municipal wastewaters are exceedingly diverse, both with respect to number of components and range of particle sizes. If wastewater is filtered through membrane or glass fiber filters (which normally allow passage of particles up to about 0.3 to 2.0 μm, depending on the particular filter used), that material passing is generally defined as soluble material; this operational definition of soluble material will be used throughout this document. References to BOD_5 will mean total BOD_5 unless specifically indicated to the contrary.

Primary effluent soluble BOD_5 typically represents from 40 to 60 percent of the BOD_5 loading to a secondary RBC system. Where fine screening is used in place of primary clarification, the soluble BOD_5 component may comprise as little as 30 to 40 percent of the BOD_5 loading to an RBC system. Municipal wastewaters receiving large and/or concentrated industrial waste flows may have soluble BOD_5 percentages that differ from these values. An RBC system must not only remove the soluble wastewater components through a combination of biological oxidation and cell synthesis, but must also agglomerate/bio-precipitate/biosorb/metabolize a substantial fraction of the **incoming particulate material if a clarified effluent of acceptable secondary quality is to be achieved.**

A tendency has evolved to focus on the removal of soluble material in RBC systems since this material is readily measurable from stage to stage, is more easily incorporated into various mathematical modelling approaches, and is a key design parameter. The designer should also be cognizant that influent particulate BOD components can potentially undergo hydrolysis by exocellular enzymes and contribute to the biodegradable organic loading. In some cases, the particulate materials remaining after final clarification exert far more influence on effluent quality than would be anticipated based solely on observation of soluble BOD_5 residuals (1).

2.3 Biology

The RBC biofilm surface is highly adsorptive, partially due to its polysaccharide nature. The biological population that inhabits each stage of an RBC train reflects the environmental and loading conditions specific to that stage; consequently, a succession of microfauna develops from stage to stage consistent with the decrease in organic loading to each succeeding stage through the train (2)(3). Simple visual observation reflects a gradation in slime thickness and color in staged systems and alone can often provide an excellent indication of process performance. The first stage in a system operating within the proper organic loading range exhibits a characteristic brownish-grey color, and terminal stages that are nitrifying normally have a characteristic reddish-bronze color (4).

The dominant growth in the first stage(s) frequently consists of zoogleal and filamentous bacteria. The protozoan population increases in diversity and abundance from stage to stage as the stage loading decreases. If systems are not covered, algal growths may be expected to develop. Certain undesirable microfauna such as the snails that flourish in some trickling filter installations may also infest RBC systems (5). In lightly-loaded stages, the growth may not be uniform and patches of bare media reflecting predation by metazoa, such as bristle worms, may appear. In single-stage systems, the predominant organisms reflect the overall unit loading with Vorticella and other stalked ciliates frequently being the dominant protozoan population when reactor soluble BOD_5 is less than 15 mg/l (6).

2.4 Mass Transfer and Kinetic Considerations

The overall performance of fixed film processes including the RBC is influenced by both mass transfer and biological kinetic considerations. Laboratory studies by Kornegay and Andrews (7) with simple substrates demonstrated that the substrate removal rate became constant after the biofilm reached a certain thickness and that further increases in film thickness need not result in increased rates of substrate removal under constant-defined feed conditions. Increases in dissolved oxygen (DO) levels did not affect the maximum removal rates in these studies. Whalen et al. (8) used a microelectrode to measure DO's in excess of 5 mg/l in the slime layers developed from a 20-mg/l nutrient broth feed. When the nutrient concentration was increased to 500 mg/l, the slime DO dropped from greater than 7 mg/l in the bulk liquid to 0.24 mg/l at a 150-μm depth in the 175-μm thick film. According to Famularo et al. (9), mass transfer resistances associated with both the liquid phase and biofilm result in significant concentration gradients from the bulk liquid to reaction sites and generally control system performance.

Before presenting the equations used to describe RBC performance, it is useful to qualitatively examine the changes occurring during media rotation. These changes can be visualized by an examination of Figure 2-1. Relative values of substrate and DO are shown for one hypothetical condition. These relative values will, of course, vary for any particular set of design conditions. When the media is exposed to the atmosphere, the liquid film boundary at the air interface immediately becomes saturated with DO as shown for Point A in Figure 2-1. This saturation in turn results in an increase in the mass of oxygen that diffuses into the biofilm. When the media is submerged, oxygen transfer can occur either into or out of the biofilm depending on the bulk liquid DO levels and the degree of mixing of the liquid film with the bulk liquid. Although it is convenient to assume that the liquid film completely mixes with the bulk liquid when the media enters the liquid from the atmosphere, the studies of Zeevelkink et al. (10) show that this is not really the case. The substrate concentrations within the biofilm are also shown to vary with position on the media, with the point of maximum substrate penetration into the biofilm occurring at the point of minimum DO level.

Organic and nitrogenous materials must be transported from the bulk liquid to the biofilm surface. The incomplete mixing of the bulk liquid with the liquid phase immediately adjacent to the biofilm surface indicates that external mass transfer resistance is an important consideration. Mathematical models commonly assume that a stagnant film layer exists and that the flux of material through this layer can be calculated as:

$$J = AD\left(\frac{\Delta S}{\Delta L}\right) \qquad (2\text{-}1)$$

where J is the flux (m/t), ΔS is the difference in concentration between the bulk liquid and the liquid film at the biofilm surface (m/L^3), ΔL is the thickness of the stagnant film (L), A is the biofilm surface area (L^2), D is the diffusion coefficient of the component of interest (L^2/t), and m, L, and t denote dimensions of mass, length, and time, respectively.

An alternate approach is to utilize a mass transfer coefficient, k_l, that incorporates the estimates of diffusion, film thickness, and any convective mass transfer effects into one parameter and results in an equation as follows:

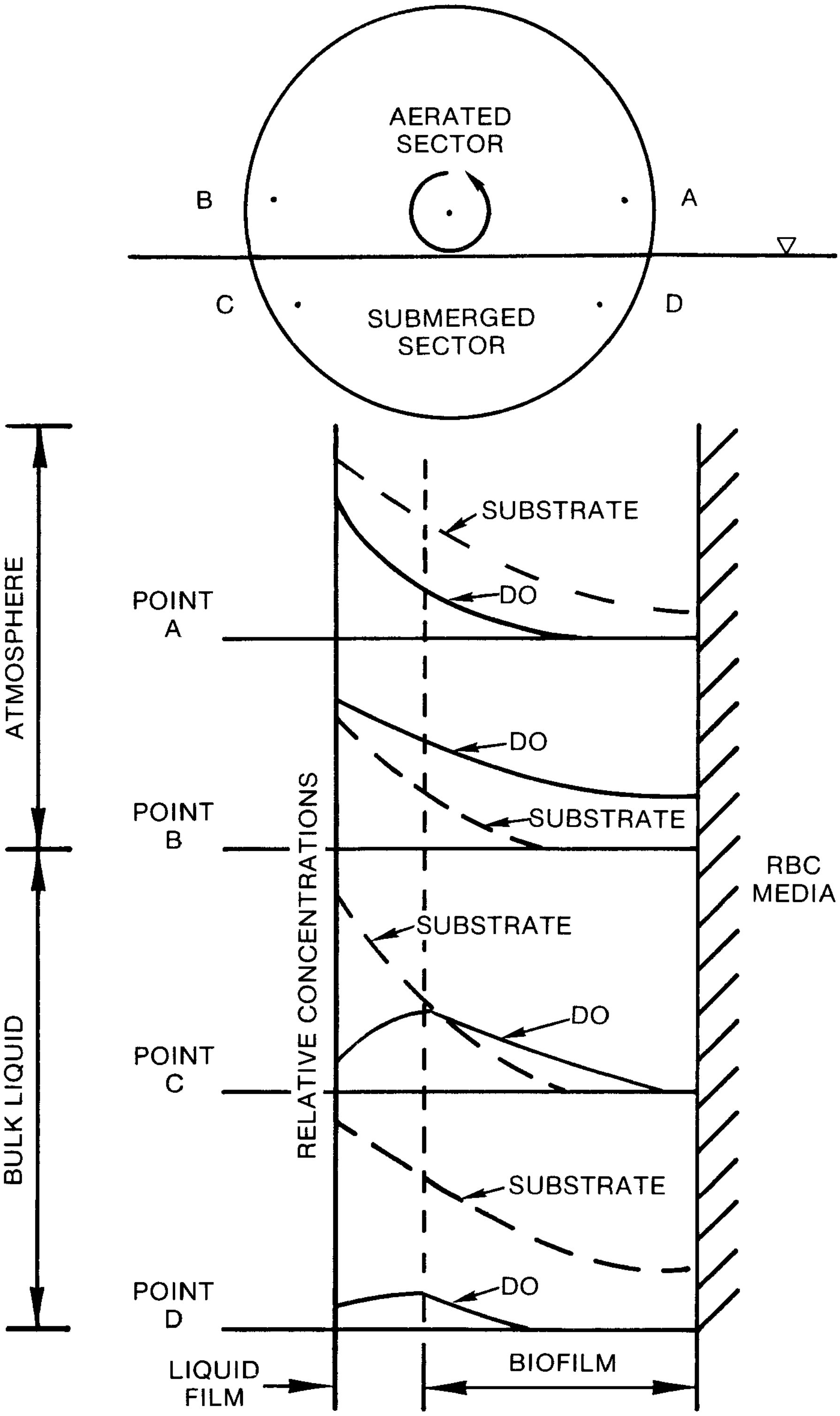


Figure 2-1. Relative concentrations of oxygen and substrate for one hypothetical loading condition and RBC rotational speed as a function of media location.

$$J = k_1 \Delta SA \tag{2-2}$$

where k_1 has dimensions of m/t.

For that portion of the rotational cycle where the media is in the air, oxygen is transferred into the liquid film adhering to the biofilm surface. The liquid film thickness is a function of rotational velocity and surface structure. In actual practice, liquid film thickness is not uniform during the air portion of the cycle since visual observation reveals a flow of water across the media/biofilm surface as the media rotates through the air.

The overall rate of reaction within the biofilm is determined by both the intrinsic reaction rates associated with the biological metabolism of the diverse number of constituents in the wastewater and the diffusion of oxygen and substrates within the biofilm. Mass transfer of either substrate or DO in the interior of the biofilm is customarily modeled by assuming that Fick's law of diffusion is applicable (9)(11)(12)(13)(14). The flux at any point can be calculated from Equation 2-1 or 2-2.

Frequently, the rate of substrate removal is modeled by an expression in which the rate is assumed to be a function of the substrate level. For example, if the substrate removal rate was controlled by substrate concentration, the Monod expression would be:

$$\left(\frac{1}{X}\right)\left(\frac{dS}{dt}\right) = k\left(\frac{S}{K_s + S}\right) \tag{2-3}$$

where X and S are the biomass and substrate concentrations (m/L^3), respectively, k is the maximum substrate utilization rate (t^{-1}), and K_s is the half-velocity constant (m/L^3). In other instances, it is more convenient to utilize either a zero-order equation:

$$\left(\frac{1}{X}\right)\left(\frac{dS}{dt}\right) = -k' \tag{2-4}$$

a first-order equation:

$$\left(\frac{1}{X}\right)\left(\frac{dS}{dt}\right) = -k'S \tag{2-5}$$

or an nth order equation:

$$\left(\frac{1}{X}\right)\left(\frac{dS}{dt}\right) = -k'S^n \qquad (2\text{-}6)$$

where k' is the reaction rate constant (dimensions vary with order of reaction) to describe the unit substrate removal rate [(1/X)(dS/dt)] as a function of substrate concentration. If S is much larger than K_s in the Monod expression, the unit substrate removal rate is essentially equal to k, i.e., zero order. Conversely, if K_s is much larger than S, the unit substrate removal rate is effectively [$(k/K_s)(S)$], i.e., first order. Thus, in many instances, either zero-order or first-order equations are good descriptors of unit substrate removal rates in the concentration ranges of interest.

For biofilms where oxygen can also limit the rates of reaction, such as a thick or heavily loaded biofilm, an expression such as:

$$\left(\frac{1}{X}\right)\left(\frac{dS}{dt}\right) = k\left(\frac{S}{K_s + S}\right)\left(\frac{DO}{K_{O_2} + DO}\right) \qquad (2\text{-}7)$$

where K_{O_2} is the half-saturation constant with respect to oxygen may be applied in which the unit substrate removal rate is taken as a multiplicative function of both substrate and DO concentrations. For a biological reaction such as nitrification where NH_3-N, oxygen, pH, and temperature are all important variables, a general unit substrate removal rate expression may take the following form:

$$\left(\frac{1}{X}\right)\left(\frac{dS}{dt}\right) = k\left(\frac{S}{K_s + S}\right)\left(\frac{DO}{K_{O_2} + DO}\right)\left(K_{20}\,\theta^{(T-20)}\right)\left(A\ pH^b\right) \qquad (2\text{-}8)$$

where $K_{20}\theta^{(T-20)}$ describes the nitrifier response over varying temperature ranges and A pH^b is a generalized expression describing the influence of pH on the nitrification rate.

If substrate removal within the biofilm is assumed to follow the Monod relationship depicted in Equation 2-3, the biomass concentration is assumed to remain constant with biofilm depth, and oxygen concentrations are not limiting, the equation for diffusional mass transfer (Equation 2-1) can be combined with that for substrate removal (Equation 2-3) to yield the following steady state equation for substrate concentration within the biofilm:

$$D\left(\frac{d^2S}{dL^2}\right) = kX\left(\frac{S}{K_s + S}\right) \qquad (2\text{-}9)$$

This nonlinear second-order differential equation does not possess an explicit solution, although numerical techniques can readily be employed to evaluate the process. An analytical solution can be obtained for either zero-order or first-order biological kinetics. When the equations are applied for substrate utilization in this form, it is assumed that the electron acceptor is not rate limiting. Oxygen transfer becomes rate limiting and controls the overall reaction rate in heavily loaded systems. The studies of Williamson and McCarty (13) in a special laboratory reactor confirmed that the mathematical approach assuming stagnant liquid layers between the bulk liquid and biofilm surface and a diffusion model for movement within the biofilm could accurately describe nitrification with biofilms of various depth and where either the electron donor or acceptor was flux and substrate limiting.

Mathematical models have been developed that consider substrate transport and metabolism and oxygen transport and depletion within the biofilm as a function of liquid film thickness, biofilm thickness, rotational speed, mixing with the bulk liquid, etc. (9)(11). The relative rates of both transport and diffusion must be considered in any generalized attempt to construct deterministic mathematical models that accurately duplicate RBC performance. An excellent discussion of the relative influence of these rates is provided by Grady and Lim (11). When all of the factors affecting substrate removal and oxygen transfer are considered, it is apparent that there is no a priori reason to expect substrate removal from the bulk liquid in an RBC system to follow any simple mathematical model.

2.5 Mass and Hydraulic Loading Variations

2.5.1 Effect on Organic Removal Performance

The design approach recommended in most situations by the RBC manufacturers to account for the impact of loading variations on organic removal is to utilize anticipated design average flows and incoming BOD_5 concentrations to determine media requirements. According to several current design manuals (15)(16), these average conditions can be used for RBC design for organic removal if the daily peak-to-average flow ratio is 2.5 or less, irrespective of the incoming mass loading pattern. If the above ratio is greater than 2.5, the manufacturers recommend the use of predicted peak hourly or daily flow for design, depending on site-specific conditions, or the provision of flow equalization.

Limited data showing RBC effluent quality changes as hydraulic and mass loadings vary are available (1)(17). In the absence of pilot plant data for a particular design in question, the basic recommendations of the RBC proprietors offer a reasonable first approach in deciding whether to utilize average or peak loading conditions for sizing media surface area to meet specific effluent limitations.

2.5.2 Effect on Nitrification Performance

Compared to heterotrophic microorganisms, nitrifying bacteria have extremely long generation times, with reported doubling periods of 8 to 17 hr (18). External accumulation and/or internal storage of substrate for delayed metabolism has not been shown to take place with nitrifiers as they do with heterotrophs. Consequently, the impact of flow and mass loading variations is more severe on the nitrification efficiency of biological systems in general than on their organic removal performance.

In assessing the effects of loading variations on nitrification performance, the attached biofilm of an RBC system represents both an advantage and a disadvantage compared to a suspended growth system. The incorporation of the nitrifying microorganisms within an attached slime resists biomass "washout" and gross loss of nitrifying capability during periods of hydraulic surging such as intense rainstorms. In contrast, hydraulic surging can displace significant fractions of activated sludge biomass to the receiving water depending on sludge settling properties and the peak hydraulic capacity of the secondary clarifier. While increased rates of biofilm sloughing and decreased nitrification efficiency are to be expected during high hydraulic throughputs, nitrifying RBC systems normally demonstrate rapid recovery following termination of the high-throughput event.

During the surge event itself, however, whether encompassing hydraulic overload, mass ammonia nitrogen overload, or both, RBC's and other fixed film processes can be anticipated to exhibit poorer nitrification efficiency than a suspended growth reactor, provided the activated sludge biomass is not "washed out" of the system. This discrepancy is attributed to the longer nominal detention times typically provided in activated sludge units and the fact that fixed film processes are assumed to be mass transfer limited while suspended growth processes are not.

Borchardt et al. (19) conducted a carefully-controlled laboratory comparison of the effects of mass loading surges caused by hydraulic shock versus concentration shock on RBC nitrification performance employing a 2-ft diameter, polystyrene, six-stage unit. The results of this experiment are summarized in Figures 2-2 and 2-3, respectively.

Examination of these two figures reveals that the pilot RBC system responded more favorably to the concentration surges than to the hydraulic surges. Increases in effluent ammonia nitrogen levels were on the order of 10 to 50 percent less for the concentration shock runs. Time for complete recovery to pre-shock performance levels, however, tended to be somewhat shorter after cessation of the hydraulic shocks.

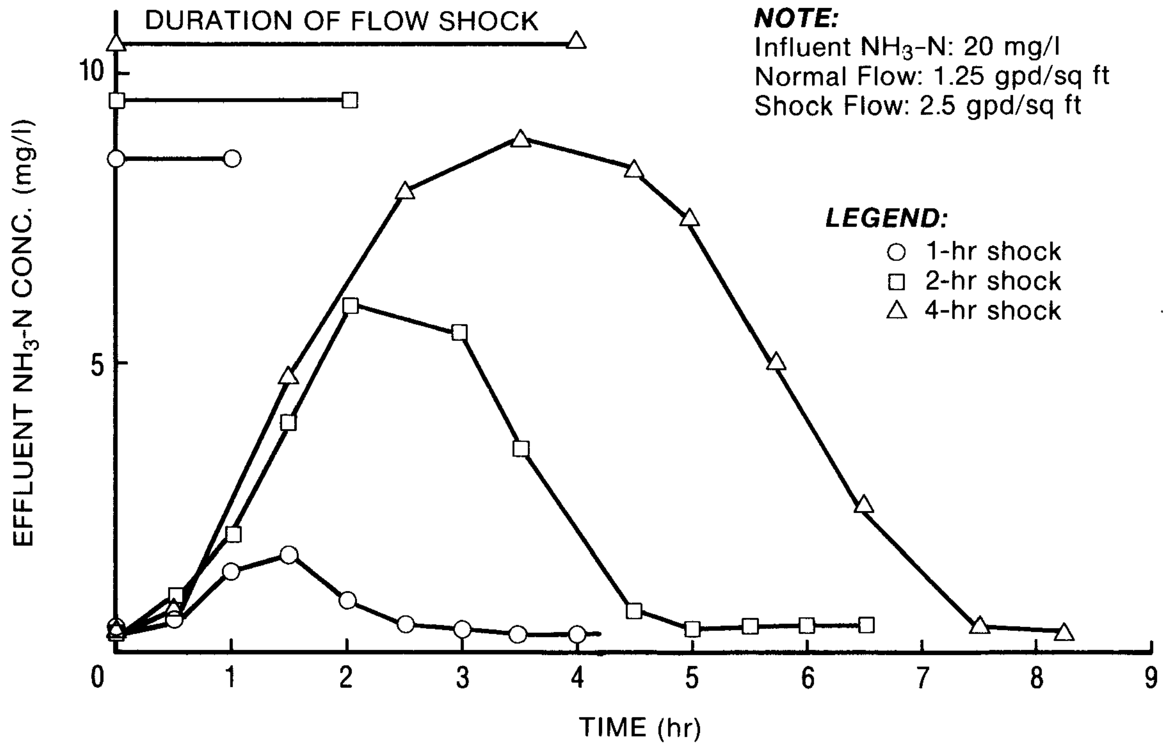


Figure 2-2. Effect of flow shocks on RBC nitrification performance [from Borchardt et al. (19)].

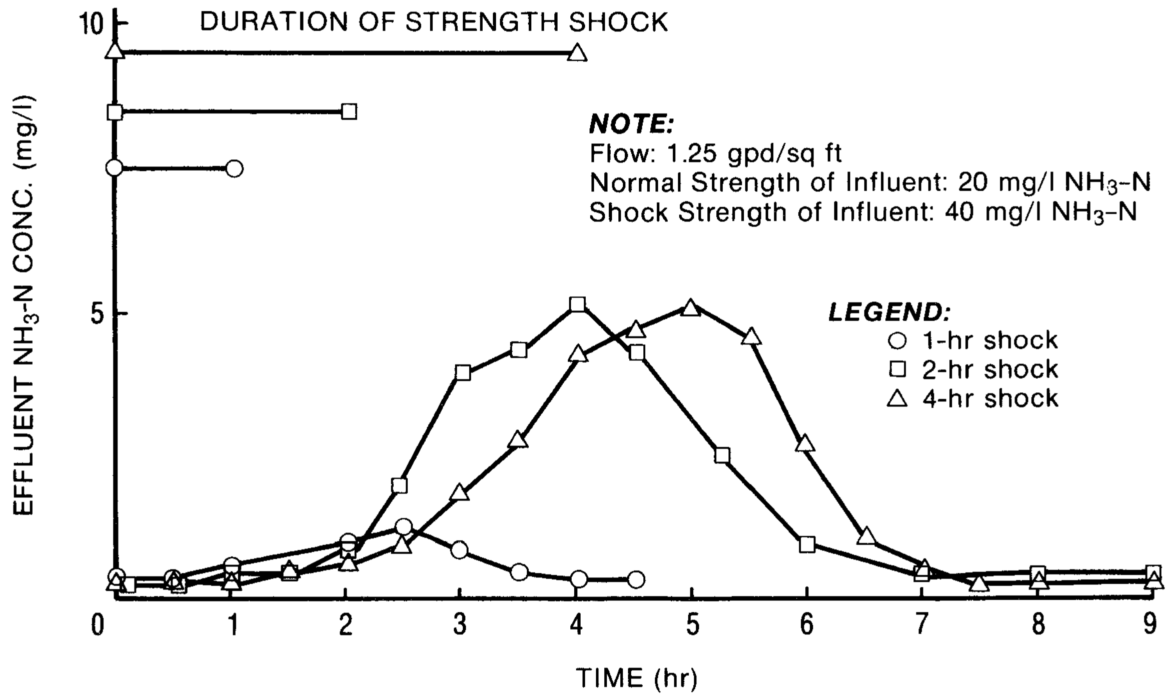


Figure 2-3. Effect of concentration shocks on RBC nitrification performance [from Borchardt et al. (19)].

For any given dry-weather diurnal flow pattern, variations in effluent concentration of unoxidized nitrogen from an RBC system will mirror variations in influent concentration, but at a lower level (dictated by the average removal or oxidation rate) and with a lag time roughly corresponding to nominal reactor detention time (approximately 2 to 3 hr for a four- to six-stage RBC reactor). This trailing pattern is readily evident in the influent and effluent TKN concentration data of Figure 2-4, adapted from Murphy and Wilson's report (1) of studies carried out on a 19.7-in. diameter pilot unit operated in the combined carbon oxidation-nitrification mode. Based on these results, they recommend that 35 percent greater media surface area be provided for a full-scale combined carbon oxidation-nitrification RBC system operating with a daily peak-to-average-to-minimum flow ratio of 2:1:0.5 than for a system with the same design hydraulic loading where prior flow equalization is provided.

The influent-effluent mirror pattern created by hourly variations in RBC mass loading (Figure 2-4) extends to daily average RBC nitrification performance as illustrated in Figure 2-5. These data were generated over a 3-1/2-mo period for the City of Indianapolis (20) on a 10.5-ft diameter nitrifying RBC pilot plant receiving biologically treated effluent as system feed. Influent ammonia nitrogen concentration varied as shown, but influent flow remained constant during selected phases at hydraulic loadings of 1.35 to 3.0 gpd/sq ft. Spikes in daily influent concentration were generally matched by time-correlated but smaller spikes in effluent concentration. Daily effluent ammonia nitrogen patterns from nitrifying activated sludge systems tend to be smoother, reflecting less correlation to influent variability.

Consideration of loading variation impacts is not critical for RBC systems designed to achieve intermediate levels of nitrification. To obtain consistently low effluent ammonia nitrogen residuals (1 to 2 mg/l), however, the aforegoing discussion strongly suggests that RBC nitrification designs should provide adequate media surface area to compensate for expected flow and concentration variability or should consider prior flow and mass equalization.

2.6 Scale-up

A common RBC design practice in the past has been to scale up small pilot plant results to full-scale applications by setting the media tip or peripheral speed at the same value for both size units, i.e., normally about 60 fpm for mechanically driven units. In doing this, media surface area was presumed to scale up directly as the key design parameter. More recent studies have shown that smaller systems exhibit greater removal capacities per unit surface area under conditions of high organic or hydraulic loading and low DO concentration. Reh et al. (21) estimated that the oxygen transfer capacity of their 18-in. diameter unit was about 1.6 times greater than

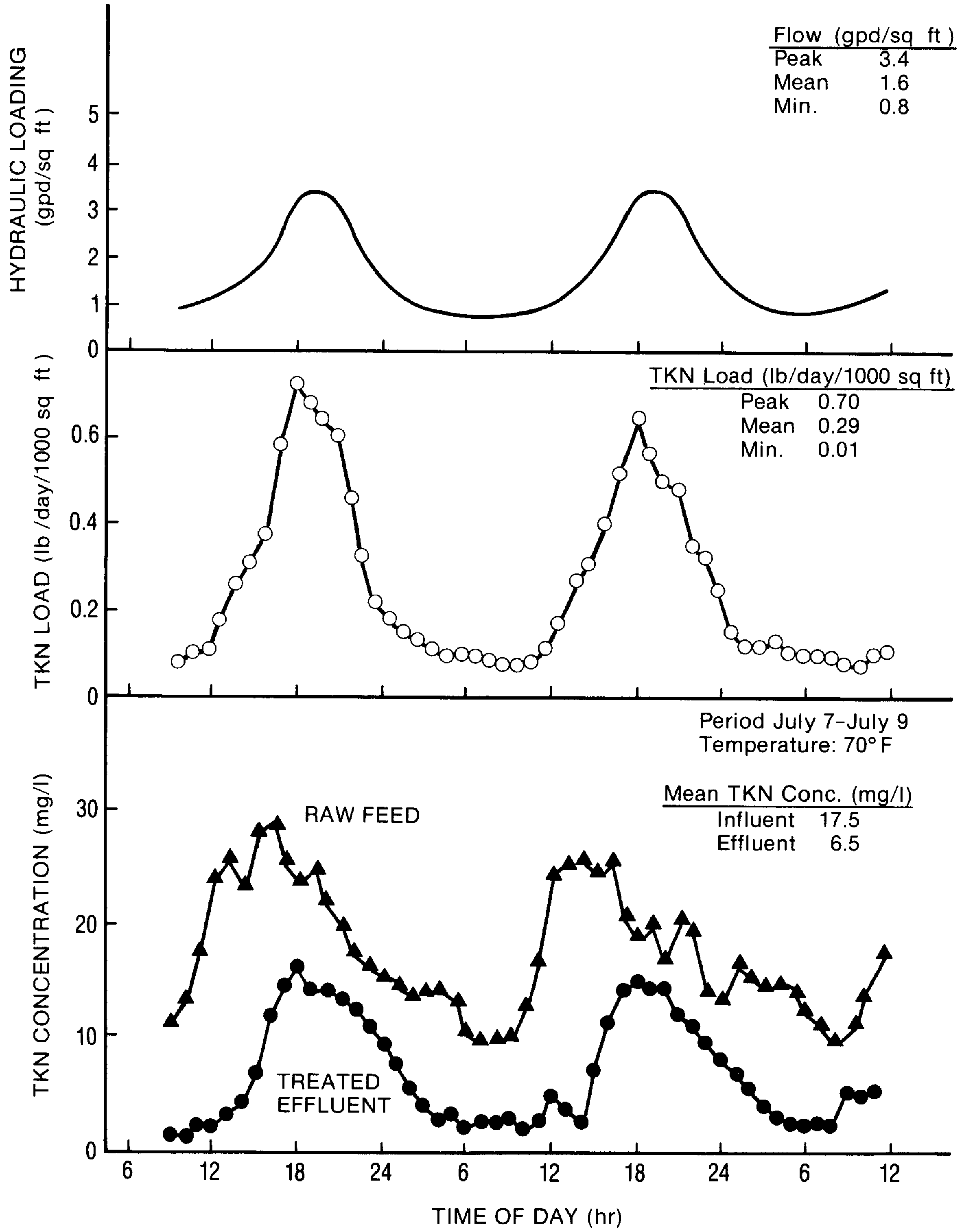


Figure 2-4. Effect of diurnal flow and concentration variations on RBC nitrification performance [adapted from Murphy and Wilson (1)].

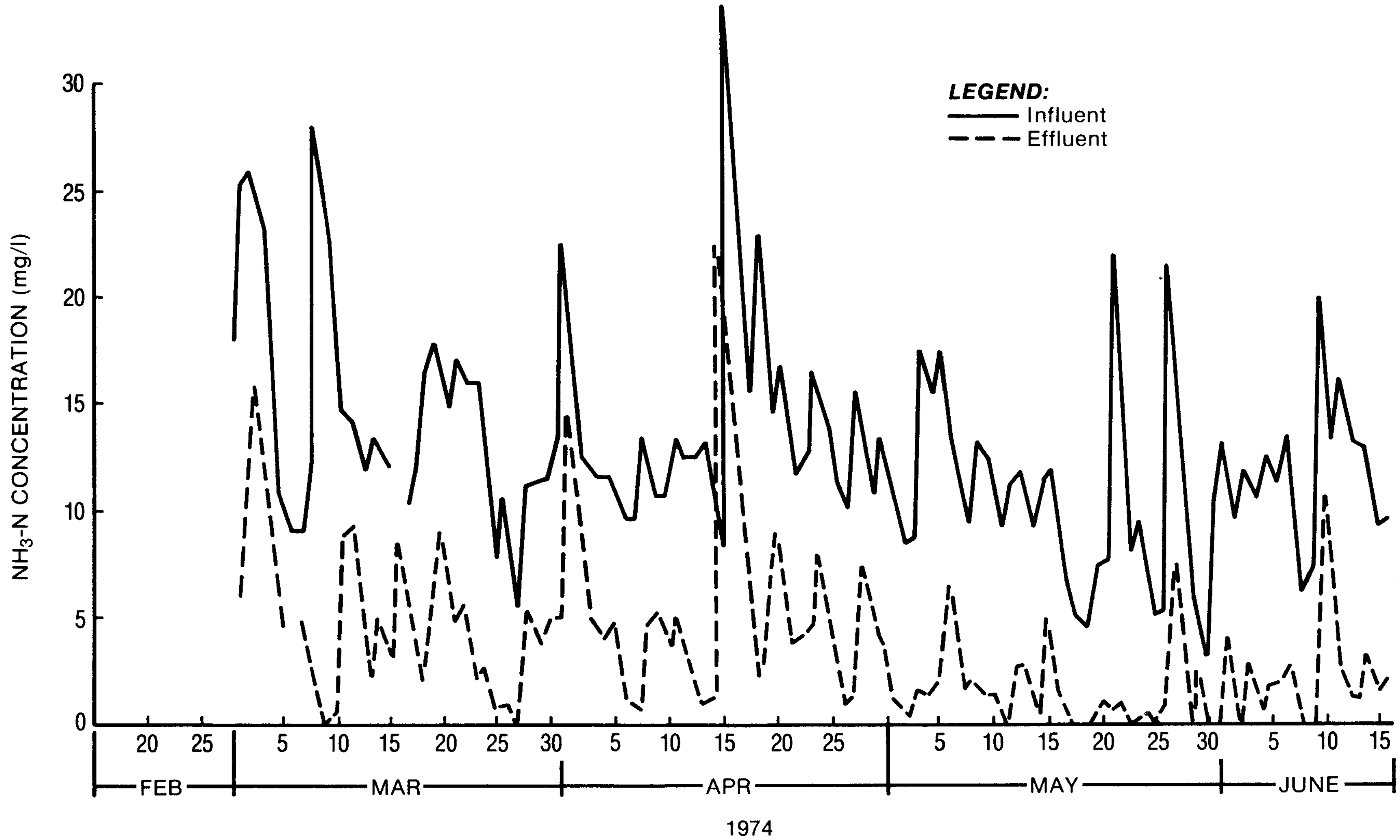


Figure 2-5. Effect of daily influent concentration variations on RBC nitrification performance at constant flow [from City of Indianapolis (20)].

that of a 10.5-ft diameter unit they evaluated. Murphy and Wilson (1) reported an average 17-percent higher mass removal of COD per unit surface area for a 1.6-ft diameter pilot RBC than for a 6.6-ft diameter unit operated at the same peripheral speed and recommended that 25 percent more surface area be provided when extrapolating 1.6-ft RBC test data to full-scale design and 10 percent more when extrapolating 6.6-ft RBC test data to full-scale design. Pilot-scale RBC nitrification data also often exhibit ammonia nitrogen removal rates 50 to 150 percent higher (19)(22)(23) than the commonly accepted full-scale removal rate of 0.3 lb NH_3-N/day/1000 sq ft (24).

The above discrepancy in removal capacities of different size RBC units may be partially explained on the basis of "relative surface renewal". "Relative surface renewal" is defined as the ratio of rotational velocity for a given unit to that of a standard 12-ft diameter unit when both are operated at the same tip speed. Depending on diameter, the angular or rotational velocity of a pilot RBC system may be several times that of a 12-ft diameter field unit at identical tip speeds. For example, the rotational velocity of a 4-ft diameter pilot unit is 4.8 rpm at the industry-standard tip speed of 60 fpm compared to 1.6 rpm for a 12-ft diameter unit, yielding a "relative surface renewal" factor of 3.0. A "relative surface renewal" factor greater than 1.0 results in more frequent exposure of a given element of biofilm to the atmosphere where the majority of oxygen transfer is indicated to take place in the RBC process (see Figure 2-1).

The high "relative surface renewal" factors associated with high rotational velocities produce the following effects in an RBC: 1) less time for depletion of substrate in the biofilm during the atmospheric portion of the cycle, 2) less time for depletion of DO in the biofilm during the submerged portion of the cycle, 3) increased turbulence at the tank air-wastewater interface, 4) lifting of thicker films of wastewater into the atmosphere, and 5) greater flow or draining of wastewater over the media and attached biofilm back to the tank during the atmospheric portion of the cycle. The latter three effects all promote higher oxygen transfer rates into the biofilm. Because there is less time for substrate depletion, the average substrate concentration in the biofilm remains higher throughout the atmospheric portion of the cycle. The higher average concentration creates a higher demand for oxygen at the wastewater film-biofilm interface, thereby increasing the oxygen transfer driving force into and across the wastewater film. Increased oxygen transfer and reduced opportunities for substrate and DO depletion undoubtedly contribute substantially to the higher substrate removal rates typically observed in RBC pilot plants as compared with full-scale RBC systems.

Insufficient information is presently available to accurately predict appropriate scale-up factors for pilot-generated RBC data (25). Very small-scale pilot units (1.5-ft diameter or less) are more useful in determining the basic treatability of a wastewater than in establishing full-scale design parameters. However, if small-diameter units must be operated to collect design data, it is important that each stage be loaded below the oxygen transfer capability of a full-scale unit to minimize scale-up considerations.

2.7 Organic Removal

2.7.1 Active Biomass

Data relating organic loading to the first stage of a full-scale RBC system and the resulting soluble BOD_5 removals and biofilm thicknesses are shown in Table 2-1. The biomass in this table was conservatively estimated by assuming a 5-percent solids concentration with a specific gravity of 1.0 for the biomass component of the attached biofilm. The generally low soluble BOD_5 removals obtained at the relatively low calculated food-to-microorganism (F/M) loadings (based on total BOD_5 applied) illustrate that mass transfer of DO and substrate are more important in controlling first-stage removals than microbial kinetic considerations.

The active biomass depth has been estimated by a number of investigators at between 20 and 600 µm (0.0008 and 0.024 in.). The shaggy biomass surface makes the definition of the active depth somewhat imprecise. Nonetheless, when these depths are compared to the biofilm thicknesses shown in Table 2-1, it is clear that the first stage(s) in a highly loaded RBC system consist of large amounts of biomass that are not contributing to the removal of organic materials in the influent wastewater. If it is assumed that the biofilm reaches an equilibrium condition, i.e., the total film thickness does not continually increase, it is possible to grossly estimate the probable range of solids retention times (SRT's) for the organisms in the rela-

TABLE 2-1. FIRST-STAGE BIOMASS AND ORGANIC REMOVAL RELATIONSHIPS*

Run	Biofilm Thickness (in.)	Biomass/1000 sq ft (lb)	F/M Loading (day^{-1})	Soluble BOD_5 Removal (%)
V-A	0.057	14.82	0.60	57
V-B	0.062	16.12	0.56	52
VI-A	0.080	20.8	0.26	57
VI-C	0.057	14.82	0.48	59
VII	0.075	19.5	0.60	22
VIII	0.110	28.6	0.32	21
IX	0.113	29.38	0.76	34

*Taken from Hynek and Chou (26).

tively thin biomass layer responsible for substrate removal from the bulk liquid. Such estimates are presented in Table 2-2 where the ranges of percent solids in the biofilm, yields, and active layer thicknesses used in the SRT calculations reflect estimated values based on several literature citations (7)(8)(9)(17)(27)(28).

Although the calculations summarized in Table 2-2 can only approximate actual conditions, they do illustrate several important points. At the highest removal rate shown, the average SRT of the biomass layer actually removing substrate from the bulk liquid is estimated to be between 0.25 and 1.5 days. Particulate BOD that becomes attached to biomass has a short average time to be degraded before the biomass particle to which it is attached leaves the biofilm and reenters the bulk liquid. It is not until the removal rate drops to between 0.5 and 1.5 lb soluble BOD_5/day/1000 sq ft that the SRT begins to reach the range that would be required for the growth of nitrifying organisms. These calculations indicate why heavily loaded RBC systems do not nitrify and also that in lightly loaded stages (<0.5 lb soluble BOD_5/day/1000 sq ft) any particulate BOD that becomes attached to the biofilm should have a sufficient average residence time in the biomass to exert a substantial oxygen demand.

2.7.2 Loading Limitations

2.7.2.1 Beggiatoa

Where DO is depleted within the biofilm, sulfate reduction and/or anaerobic decomposition of the solids can occur. Anaerobic decomposition products

TABLE 2-2. ORGANIC REMOVAL AND ESTIMATED BIOLOGICAL SRT's FOR RBC SYSTEMS

Soluble BOD_5 Removal Rate for any Stage (lb/day/1000 sq ft)	Estimated SRT of Active Biomass Layer (days)	Range of Conditions Considered in SRT Calculations		
		% Solids in Biofilm	Yield $\left(\frac{g\ SS}{g(BOD_5)_R}\right)$	Active Layer Thickness (µm)
2.5	0.25- 1.5	5-10	0.8-1.0	60-150
1.5	0.49- 3.2	5-10	0.8-1.0	70-180
0.5	2.0 -13.6	5-10	0.6-1.0	100-200
0.1	10-153	5-10	0.4-1.0	100-300

can diffuse back from deep within the biofilm into the active biofilm depth, in effect producing an additional oxygen demand from the media side. When sulfate is reduced, the relative proportions of HS^- and H_2S existing in equilibrium are pH dependent. At pH 7.0, 50 percent will exist as HS^- and 50 percent as H_2S for the temperatures and conductivities associated with municipal wastewater. Overall, each mole of sulfate that is reduced to sulfide and then reoxidized and deposited as elemental sulfur releases a net 1.5 moles O_2.

When sulfide is present, either in the influent wastewater or by its production deep within the biofilm, sulfide oxidizing organisms such as Beggiatoa can and frequently do grow on the biofilm surface (29). The questions of autotrophy in Beggiatoa and the relative influences of H_2S and DO concentrations on growth rate are not yet clarified. The organism will grow readily as a heterotroph on a number of dilute organic substances. A number of strains require H_2S for growth (30). Beggiatoa deposit sulfur granules within the cell in the presence of oxygen.

Beggiatoa compete with heterotrophic organisms for oxygen and space on RBC media surface. Their predominance can result in an increase in the concentration of biomass on an RBC unit while at the same time causing a substantial reduction in organic removal per unit area. In extreme cases, the takeover of the first stage of an overloaded RBC system by Beggiatoa can shift the load to the next stage leading to a progressive Beggiatoa takeover of the entire system and significant deterioration of effluent quality.

In the absence of a biological sulfide oxidation problem such as produced by Beggiatoa, an organically overloaded RBC stage may well be operating at the maximum substrate removal rate possible. The rate will be controlled by oxygen transfer into the biofilm. As Beggiatoa or other sulfide oxidizing organisms become predominant and/or excessive anaerobic metabolism occurs within the biofilm interior, the overall organic removal rate may be expected to fall from the maximum possible bulk liquid substrate removal rate.

2.7.2.2 Oxygen Transfer

Oxygen is transferred directly from the atmosphere into the attached wastewater film and biofilm on that portion of the RBC media exposed to the atmosphere. In addition, oxygen enters the bulk liquid from direct transfer due to turbulence generated by rotation of the media and by the return to the bulk liquid of the attached wastewater film and other wastewater lifted into the atmospheric sector that flows freely across the media. Where organic removals in the first stage of heavily loaded systems have been limited by DO availability, it has been shown that increasing the oxygen content in the gas phase will increase the organic removal rate

(31)(32)(33). Gas transfer from the air directly into the attached wastewater and biofilms represents the major oxygen source for the organisms.

Some researchers have attempted to develop procedures to predict oxygen transfer into the bulk liquid and to relate these transfer coefficients to system geometry. Using clean water test data, Severin et al. (34) were able to relate a dimensionless oxygen transfer parameter to a Reynolds number based on net water velocity and tank parameters. Scale-up based on tip speed or surface area turnover was shown to be inadequate. Increasing tip speed from 1.2 to 1.6 rpm increased oxygen transfer from 2.3 to 3.8 g O_2/min with the 66-sheet, 11.7-ft diameter media packs employed.

Measurements of oxygen transfer coefficients for gas transfer into the RBC bulk liquid do not provide a meaningful or useful indicator of system potential. If oxygen transfer from the gaseous phase into the wastewater film with subsequent diffusion into the biofilm is much more important than transfer from the bulk liquid into the biofilm as suggested by Huang (35), then bulk liquid oxygen transfer coefficients are not a useful measure of oxygen transfer occurring in an RBC system. While low bulk liquid DO's or falling DO's from stage to stage are indicative of an overloaded system (36), increasing DO levels in the bulk liquid will not necessarily overcome process performance difficulties that may develop. Two of the plants studied by Chesner and Iannone (36) had nuisance organisms (Beggiatoa) present in the first stages despite bulk liquid DO levels of 1.5 to 2 mg/l. A similar observation was also made at an RBC facility in Edgewater, New Jersey (17). A major advantage of the air drive RBC system is claimed to be related to the increased turbulence and stripping of excess biofilm as a portion of the air bubbles rise through the media. This aspect may be of substantially more benefit to system performance in heavily loaded systems than small increases in bulk liquid DO levels afforded by the air drive mechanism.

A major constraint in the design of any RBC system is limiting the loading to the first stage(s) to values compatible with the oxygen transfer capability of the system. Exceeding this capability will often result in the proliferation of sulfide oxidizing organisms that leads to overall process deterioration. Chesner and Iannone (36) surveyed 23 RBC installations and related the presence of sulfide oxidizing organisms to overloading caused by high hydraulic loading and/or high influent BOD concentrations. Their survey results are summarized in Figure 2-6. It can be seen that a first-stage loading limit in excess of 6.4 lb total BOD_5/day/1000 sq ft was associated with the presence of sulfide oxidizing organisms. This loading should correspond to a soluble BOD_5 loading in the range of 2.6 to 3.8 lb/day/1000 sq ft.

According to the Autotrol design manual (15), the first-stage loading limit for a mechanically driven shaft is 4 lb soluble BOD_5/day/1000 sq ft. Cases

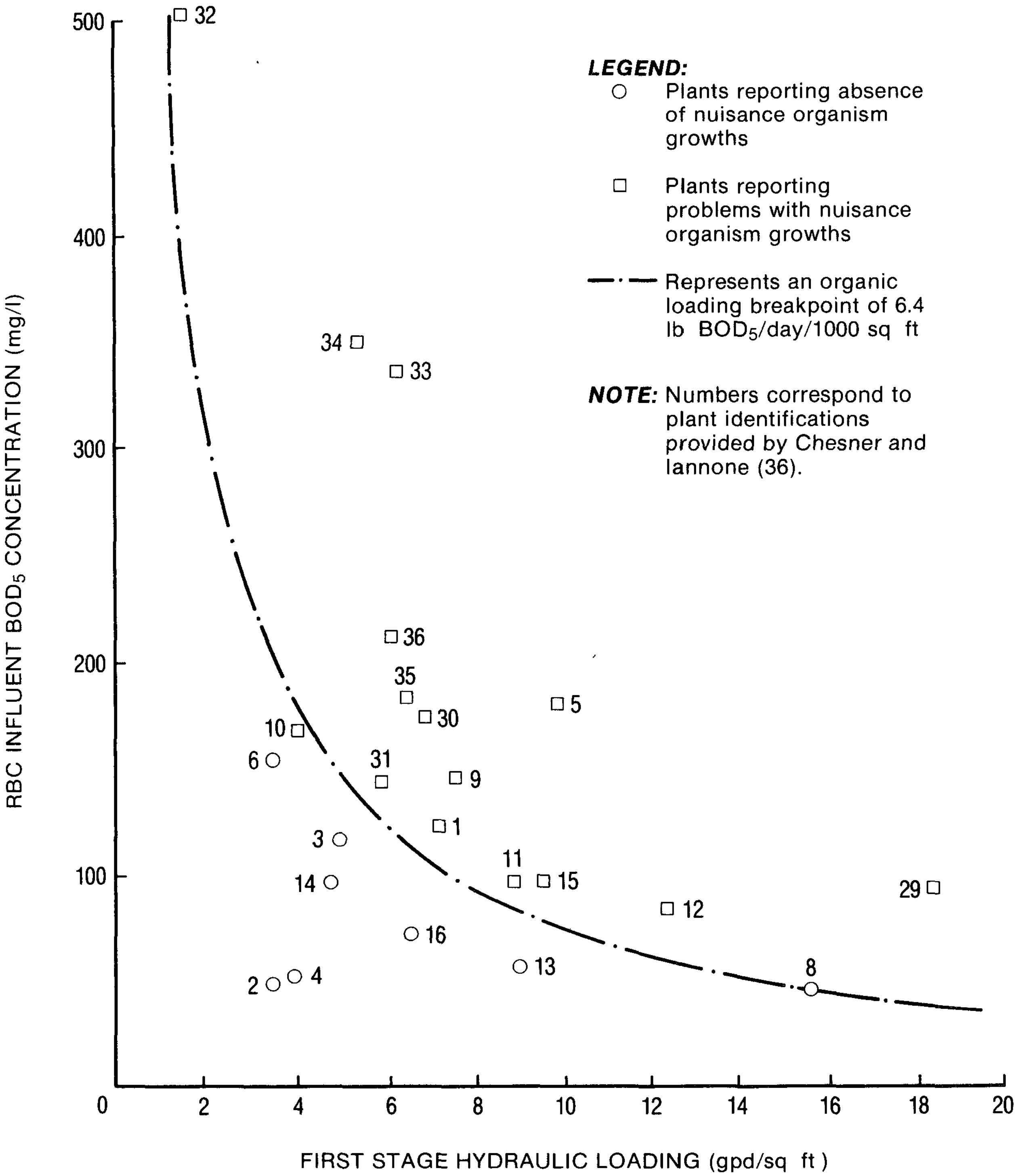


Figure 2-6. DO limiting conditions related to influent organic concentration and hydraulic loading [from Chesner and Iannone (36)].

have been reported, however, where RBC first-stage oxygen transfer capabilities were exceeded above loadings of 3 lb soluble BOD_5/day/1000 sq ft (37).

Supplemental aeration of the bulk liquid is reported to increase allowable loadings (37), but it does not assure elimination of nuisance organisms even in the presence of adequate bulk liquid DO as established by the observations of Chesner and Iannone (36). It would be expected, however, that the dominance of nuisance organisms would tend to decrease with increasing bulk liquid DO levels. Supplemental aeration studies conducted by Chou (38) using mechanically driven units, clean media, and tap water indicated that the oxygen transfer efficiency for the coarse bubble system installed was 2 to 2.5 percent.

The Autotrol design manual (15) also indicates that zero-order removal of soluble BOD_5 at a maximum rate of 2.5 lb/day/1000 sq ft is possible for mechanically driven units and 3 lb/day/1000 sq ft may be achieved with air driven units. In the zero-order removal range, BOD removal is controlled by oxygen diffusion (15). Consider the first-stage data obtained by Hynek and Chou (26) using 11.8-ft diameter discs (12,500 sq ft/stage) to treat municipal wastewater at Milwaukee County's South Shore Wastewater Treatment Plant and summarized in Table 2-3. A maximum soluble BOD_5 removal of about 2.6 lb/day/1000 sq ft was achieved. It is clear, however, that soluble BOD_5 removal was not constant, nor was it a single-valued function of bulk liquid soluble BOD_5 concentration. The periods of lowest removal were partially related to periods of greatest biofilm thickness.

Soluble COD removal data obtained at the overloaded Brookville, Indiana RBC plant by Opatken (39) indicated zero-order removal of soluble COD in each of the four stages at a rate of 2.5 lb/day/1000 sq ft. This removal rate is about one-half the expected maximum rate (assuming a typical soluble COD:soluble BOD_5 ratio of 2); however, this plant is routinely plagued by a proliferation of Beggiatoa growth. Use of a clarigester (sludge storage) for pretreatment at Brookville may contribute sulfide to the RBC reactor influent.

The total COD reduction across an RBC stage is a direct measure of oxygen transfer capability, provided that nitrate or sulfate reduction is not occurring and stage influent and effluent DO levels are the same. Full-scale measurements of total COD removal across a stage are virtually impossible to find in the literature. Scheible and Novak (40) measured total COD removal and the COD equivalent of the settled solids to estimate the total oxygen utilization rate. Their results are presented in Figure 2-7. These data were obtained with full-scale media on 13.5-ft long shafts and indicate a maximum oxygen utilization rate of 1.4 to 1.5 lb O_2/day/1000 sq ft with this rate limitation also reflecting the maximum oxygen transfer capability of the system.

TABLE 2-3. FIRST-STAGE RBC DATA REPORTED BY HYNEK AND CHOU (26)

Run No.	Waste-water Temp. (°F)	Total BOD_5 Applied $\left(\frac{lb/day}{1000\ sq\ ft}\right)$	Mechanical Drive Soluble BOD_5			Total BOD_5 Applied $\left(\frac{lb/day}{1000\ sq\ ft}\right)$	Air Drive Soluble BOD_5		
			Applied $\left(\frac{lb/day}{1000\ sq\ ft}\right)$	Removed $\left(\frac{lb/day}{1000\ sq\ ft}\right)$	in Reactor (mg/l)		Applied $\left(\frac{lb/day}{1000\ sq\ ft}\right)$	Removed $\left(\frac{lb/day}{1000\ sq\ ft}\right)$	in Reactor (mg/l)
V-A	53	8.85	4.25	2.41	41	10.0	4.82	2.59	44
V-B	59	8.98	2.86	1.5	40	10.2	3.25	1.93	34
VI-A	73	5.50	2.52	1.44	31	5.39	2.47	1.65	24
VI-B	64	-	1.29	0.76	16	-	1.34	0.93	12
VI-C	66	7.08	2.50	1.47	32	7.45	2.63	1.42	36
VII	65	11.7	4.20	0.94	45	12.1	4.31	1.16	43
VIII	63	9.16	3.54	0.76	40	9.34	3.61	1.13	35
IX	57	22.4	6.26	2.14	44	23.4	6.53	2.53	41
X	54	-	5.54	1.78	53	-	5.65	1.59	56

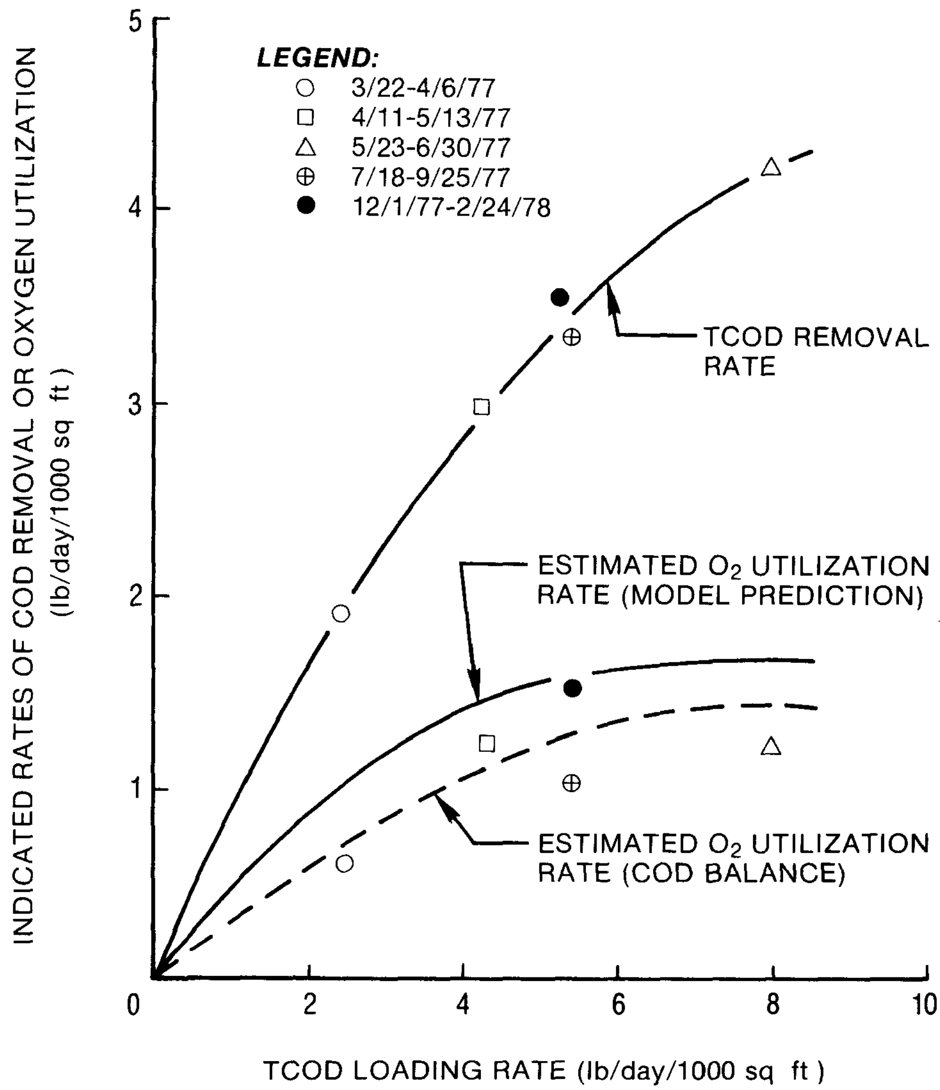


Figure 2-7. Estimate of RBC oxygen utilization rates [from Scheible and Novak (40)].

In summary, an organically overloaded RBC stage can lead to heavy biofilm thickness and/or proliferation of nuisance organisms such as Beggiatoa that result in a net decrease in organic removal across the stage. When designing a mechanically driven RBC system, research and field observations indicate that safe, conservative loading figures for first-stage loading are 2.5 lb soluble BOD_5/day/sq ft or 6 lb total BOD_5/day/1000 sq ft. These figures may be increased, but the designer must recognize that this increase may lead to heaver-than-normal biofilm growth, bulk liquid DO depletion, development of nuisance organisms, deterioration of overall process and/or mechanical performance, etc. A first-stage loading exceeding the above figures may be justified depending on the degree of operational and maintenance attention the plant will receive, the structural capacity of the selected shaft, the ability to strip excess biomass from the media, the levels of sulfur compounds in the RBC system influent, the media surface area required in the remaining stages, and the ability to vary the operational mode of the plant. The loading, however, should generally not exceed 4 lb soluble BOD_5/day/1000 sq ft or 8 lb total BOD_5/day/1000 sq ft.

2.7.3 Additional Factors Affecting Organic Removal

In addition to the performance variations observed when treating the same wastewater with different diameter units at equivalent loadings, a number of other factors affect the performance of RBC systems and influence the results observed. Some of these factors are discussed below.

2.7.3.1 Tank Volume-to-Media Surface Area Ratio (Detention Time)

Based largely on work with 2- to 6-ft diameter RBC pilot units, Antonie (4) observed that increases in the tank liquid volume-to-media surface area ratio beyond 0.12 gal/sq ft did not increase percent BOD removal at a given hydraulic loading rate (gpd/sq ft of media). Use of different tank configurations and tank volume-to-media surface area ratios will result in differences in oxygen transfer into the bulk liquid, the degree of mixing, the amount of dead space in the tank, and hydraulic retention time at a given flow rate, all of which can affect a comparison of the results obtained from various pilot- and full-scale studies.

2.7.3.2 Number of Stages

Studies conducted by Antonie (4) with 5.74-ft diameter discs clearly demonstrated that a four-stage RBC unit produced higher percentage BOD and suspended solids removals than obtained with a two-stage unit having the same overall surface area when treating the same municipal wastewater over a hydraulic loading range of 1 to 5 gpd/sq ft. For hydraulic loadings below 5 gpd/sq ft, four- and six-stage operation produced virtually identical performance. Soluble organic loading data were not collected during these studies.

For any kinetic order higher than zero, overall carbonaceous removal for a given media surface area will be enhanced by increasing the number of stages. When selecting the number of stages for an RBC system design, however, the primary consideration is to ensure that the organic loading to any individual stage is not excessive, i.e., not greater than 2.5 lb soluble BOD_5/day/1000 sq ft. If the design selection calls for a one-stage system at a low overall organic loading, there is no reason to automatically add several additional stages. In reality, stage selection is an integral part of the overall design process and the staging recommendations provided in the manufacturers' design manuals should be used with discretion. The current staging recommendations of three of the manufacturcturers are summarized below.

Autotrol (15)		Clow (16)	Lyco (41)	
Target Effluent Soluble BOD_5 (mg/l)	Recommended Minimum No. of Stages	At least four stages per flow path recommended	Target Total BOD_5 Reduction	Recommended No. of Stages
>25	1		up to 40%	1
15-25	1 or 2		35 to 65%	2
10-15	2 or 3		60 to 85%	3
<10	3 or 4		80 to 95%	4
			Minimum of four stages recommended for combined BOD_5 and NH_3-N removal	

2.7.3.3 Wastewater Temperature

Studies reported by Antonie (4) indicated that organic removal efficiency was unaffected by wastewater temperatures above 55°F, but process performance deteriorated at lower temperatures. The temperature correction curve developed by Autotrol (6) assumed that a theta (θ) value of 1.05 should be applied below 55°F since this value is commonly associated with biological systems. However, because the organic removal rate in an RBC system is controlled by mass transfer rates of oxygen and substrate in addition to biological kinetics, the utilization of a temperature correction factor based solely on biological kinetic considerations is questionable. Below about 50°F, variations in the temperature correction factors recommended by the manufacturers for carbonaceous removal become increasingly pronounced with decreasing temperature as illustrated in Figure 2-8 (42). The manufacturers' surface area correction factors are referenced to a wastewater temperature of 55°F.

In some highly loaded RBC systems, lower wastewater temperatures do not always result in decreased carbonaceous removal rates and, in fact, may

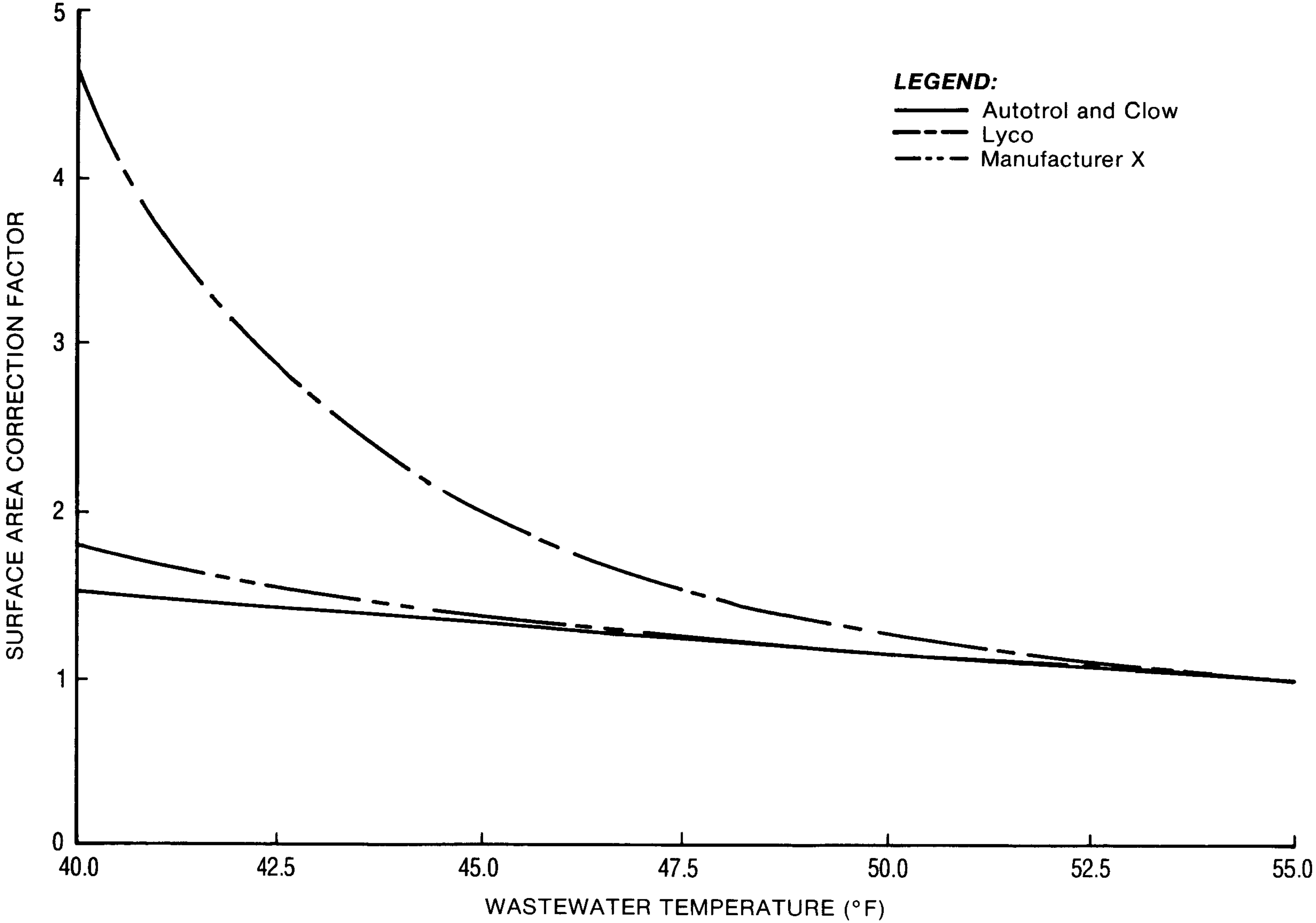


Figure 2-8. Manufacturer temperature correction factors for BOD_5 removal [from Roy F. Weston (42)].

enhance removals. When this phenomenon occurs, it can be attributed to increasing DO saturation values with decreasing temperature, which promote increased oxygen transfer, and possible reduction in the concentration of sulfide oxidizing organisms. For example, Scheible and Novak (40) obtained the following essentially equivalent overall performance data under summer and winter conditions with 12-ft diameter RBC units:

Parameter	Summer	Winter
Hydraulic loading (gpd/sq ft)	2.1	2.0
Organic loading (lb total BOD_5/day/1000 sq ft)	2.3	2.6
Wastewater temperature (^{o}F)	79	52
Effluent total BOD_5 (mg/l)	28	33
Effluent soluble BOD_5 (mg/l)	23	24

Others (6) have reported increased removals in wintertime conditions for heavily loaded systems, such as at Alexandria, Virginia.

2.7.3.4 Influent Wastewater Concentration

In general, percentage BOD removal for municipal wastewater increases at a given hydraulic loading as the wastewater strength increases. For high strength industrial wastewaters, this often is not the case. These general trends have been reported by the ASCE RBC Task Committee (43) and Chesner and Iannone (36). Thus, a comparison of systems on the basis of percent removals where different wastewater strengths are involved can be misleading.

2.8 Nitrification

2.8.1 Overview

The internally-staged configuration of an RBC system, which promotes sequential or plug flow removal of substrate, is conducive to the development of a nitrifying bacterial population. The degree of this development in any stage depends primarily on the soluble organic concentration in the stage bulk liquid. Population dynamics dictate that heterotrophs, i.e., bacteria that derive their energy from the oxidation of organic carbon, will predominate in an RBC biofilm when the organic concentration is high and the average SRT is low. As the organic concentration decreases to a level where the growth rate of the nitrifiers is greater than the rate of active biofilm sloughing, the percentage of nitrifying bacteria in the biofilm will increase to a point where efficient nitrification is possible. In the RBC process, the organic concentration transition point where incipient nitrification is generally observed is approximately 15 mg/l of soluble BOD_5 or 30 mg/l of total BOD_5 in the stage bulk liquid (15)(16)(41)(44).

In combined carbon oxidation-nitrification RBC systems for treatment of primary effluent, a small fraction of the incoming unoxidized nitrogen (10 to 20 percent) is utilized in the lead stages to satisfy the cell growth requirements of the predominant heterotrophic population. For municipal wastewater applications, the soluble BOD_5 concentration is typically reduced to 15 mg/l or less by the second or third stage. Depending on other environmental conditions, principally wastewater temperature, DO, and pH, significant nitrification generally begins in the third or fourth stage. From these stages on, disappearance of ammonia nitrogen is due mainly to oxidation to nitrate nitrogen rather than to heterotrophic metabolism. The onset of nitrification is noted by the appearance of nitrite and/or nitrate nitrogen in the stage liquid. In most systems, the nitrification rate in the transition stage is less than in the subsequent stage where soluble BOD_5 decreases to 10 mg/l or less. If sufficient stages are provided to achieve low ammonia nitrogen residuals (1 to 2 mg/l), the nitrification rate in the final stage(s) will be markedly reduced because of ammonia nitrogen limitations.

RBC's are also utilized for nitrification of secondary-quality effluent. Separate-stage systems of this type (not to be confused with the internal stages of an RBC reactor) are designed to protect the nitrifying population from major competition with heterotrophs. In this application, the soluble BOD concentration entering the second-stage RBC reactor is sufficiently low that maximum nitrification rates are usually established on the lead RBC shaft. First-stage options employed ahead of the RBC unit include a variety of activated sludge and attached growth processes. Separate-stage RBC nitrification is generally employed as an add-on step to existing biological treatment systems that are faced with meeting an ammonia nitrogen or TKN effluent limitation.

2.8.2 Nitrification Reactions

Nitrification is an autotrophic process, i.e., energy for bacterial growth is derived by the oxidation of inorganic nitrogen compounds, primarily ammonia nitrogen. In contrast to heterotrophs, nitrifiers utilize carbon dioxide (inorganic carbon) rather than organic carbon for synthesis of new cells. Nitrifier cell yield per unit of substrate metabolized is many times smaller than for heterotrophs. This factor accounts for the small percentage of nitrifiers in a biofilm developed on a substrate high in organic carbon.

Although a variety of nitrifying organisms exist in nature, the two genera of importance in wastewater treatment are *Nitrosomonas* and *Nitrobacter*. *Nitrosomonas* oxidize ammonia nitrogen to nitrite nitrogen. Nitrite nitrogen is subsequently oxidized to nitrate nitrogen by *Nitrobacter*.

Excellent reviews of the energy and synthesis relationships associated with biological nitrification are presented in the EPA Process Design Manual for Nitrogen Control (45) and elsewhere (46)(47)(48)(49). Overall oxidation and synthesis-oxidation reactions are developed in these documents.

Based on the overall oxidation reaction, theoretical alkalinity destruction in the nitrification process is 7.14 mg (as $CaCO_3$)/mg NH_3-N oxidized. If the minor effect of cell synthesis is considered, this value decreases to 7.07 mg (as $CaCO_3$)/mg NH_3-N oxidized. The more conservative ratio of 7.14 is recommended for engineering calculations (45).

Similarly, based solely on the overall oxidation reaction, the theoretical oxygen requirement for nitrification is equal to 4.57 mg O_2/mg NH_3-N oxidized. This theoretical requirement decreases to 4.19 mg O_2/mg NH_3-N oxidized if both oxidation and synthesis are considered. Again, a conservative ratio of 4.6 is recommended for engineering calculations (45).

2.8.3 Nitrifying Biofilm Characteristics

Stratta and Long (50) in pilot studies conducted primarily to determine the effect of pH on RBC nitrification also carried out correlative investigations of biofilm development and microbial enumeration. Their 19.7-in. diameter pilot reactors treated sidestreams of clarified trickling filter effluent with a soluble BOD_5 concentration that varied between 5 and 10 mg/l. Biofilm characteristics reported by the investigators are considered to be representative of typical separate-stage RBC nitrification.

Within 5 to 10 days after startup from clean media, Stratta and Long observed the development of thin, highly uniform textured coatings of biofilm, tan to bronze in color. Film thickness increased (and color darkened) with aging, reaching equilibrium depths after 25 to 60 days of operation. Initial sloughing was noticed within 2 to 3 wk, with texture beginning to lose its uniformity and becoming increasingly patchy with time. Maximum ammonia nitrogen oxidation rates were established within 3 to 4 wk at 58^{o}F, increasing no further even though biofilm depth continued to increase in most cases for several weeks.

Stratta and Long estimated the active depth of mature nitrifying RBC biofilm at 50 to 300 µm (0.002 to 0.012 in.), or about half of the maximum active depth cited earlier for heterotrophic growth in Section 2.7.1. Crawford's estimates (22) of overall biofilm thickness for an eight-shaft nitrifying system varied from 900 µm (0.035 in.) on the first shaft to 300 µm (0.012 in.) on the eight shaft, suggesting as with heterotrophic growth that a substantial fraction of the attached biomass in a nitrifying RBC is not active.

Based on the methodologies employed, the concentrations of heterotrophs and ammonia nitrogen oxidizers were projected by Stratta and Long to be roughly of the same order of magnitude, i.e., around 1×10^{11} bacteria/dry volatile gram (dvg) of biofilm. The concentration of nitrite nitrogen oxidizers was approximately an order of magnitude less, i.e., around 1×10^{10} bacteria/dvg or slightly lower. Nitrifiers were enumerated by the MPN technique and heterotrophs by plate counts. These data reflect considerably higher concentrations than Ito and Matsuo's work (51), which enumerated 2 x 10^6 Nitrobacter/dry gram (dg), 2 x 10^7 Nitrosomonas/dg, and 2 x 10^9 heterotrophs/dg in nitrifying RBC biofilm.

2.8.4 Factors Affecting Nitrification

2.8.4.1 Growth Kinetics

Nitrification growth kinetics and substrate utilization have been described by various methods. The most frequently used method is the following Monod expression:

$$\mu = \hat{\mu}\left(\frac{S}{K_S + S}\right) \qquad (2\text{-}10)$$

where μ is the growth rate of either Nitrosomonas or Nitrobacter (day^{-1}), $\hat{\mu}$ is the maximum growth rate of either Nitrosomonas or Nitrobacter (day^{-1}), K_S is the half-saturation constant (mg/l), i.e., the substrate (ammonia nitrogen) concentration at half the maximum growth rate, and S is the growth-limiting substrate (ammonia nitrogen) concentration (mg/l). The above equation assumes no mass transfer or oxygen transfer limitations; nitrifier growth rate is controlled only by the prevailing nitrogen substrate concentration and the microorganism's ability to metabolize or oxidize that substrate.

Values of K_S found in the literature for Nitrosomonas and Nitrobacter are typically equal to or less than 1 mg/l at liquid temperatures of 68°F or less (45), although Downing and coworkers (52)(53) have reported a K_S of 1.25 mg/l for Nitrobacter in river water at 68°F. The following estimates of $\hat{\mu}$ for Nitrosomonas and Nitrobacter can also be found in the literature:

$\hat{\mu}$ Values (day^{-1})				
Nitrosomas	Nitrobacter	Medium	Liquid Temp.(°F)	Ref.
1.08	1.44	Activated sludge	73	54
0.37	-	Activated sludge	73	55
0.85	-	Activated sludge (washout)	70	49
0.7	1.1	River water	68	52,53
0.3	-	Activated sludge	68	52,53
0.5	-	Activated sludge	68	56
0.71	-	Activated sludge	68	57
0.57	-	Activated sludge	61	58
0.40	-	Activated sludge (washout)	54	49

Most researchers have found $\hat{\mu}$ and K_S to increase with increasing liquid temperature. Estimates of $\hat{\mu}$ and K_S for attached growth biological treatment processes are conspicuously absent in the literature, but would be expected to approximate those of suspended growth cultures where mass transfer of ammonia nitrogen and DO are not limiting.

The above data generally indicate that the maximum growth rate of Nitrobacter is somewhat larger than that of Nitrosomonas, and, therefore, the oxidation of ammonia nitrogen to nitrite nitrogen is the rate-limiting reaction in nitrification. This conclusion is supported by the lack of accumulation of nitrite nitrogen in mature nitrifying systems at concentrations encountered in municipal wastewaters. The low reported K_S values for both organisms suggest that nitrifiers are reproducing at or near their maximum growth rates at nitrogen concentrations equal to or greater than 1 mg/l in the absence of limiting factors such as low DO, low pH, etc. (59).

2.8.4.2 Kinetic Models for Ammonia Nitrogen Removal

Several investigators have modified the Monod growth equation to predict rates of ammonia removal (oxidation) in the RBC process. Pano et al. (23) adapted the Monod equation to the mass removal rate of nitrogen for nitrification data generated on 15-in. diameter, polyethylene-disc RBC pilot plants treating the equivalent of primary effluent:

$$Z = k_N \left(\frac{C_i}{K_N + C_i} \right) \tag{2-11}$$

where Z is the mass removal rate of ammonia nitrogen (lb/day/1000 sq ft), k_N is the ammonia nitrogen maximum removal rate (lb/day/1000 sq ft), K_N is the ammonia nitrogen removal half-saturation constant (mg/l), and C_i is the ammonia nitrogen concentration in the ith stage (mg/l). This equation substitutes ammonia removal rate terms for the nitrifier growth rate terms of Equation 2-10. The linear regression curves (discussed further in Section 5) fitted by Pano et al. to their data indicated higher removal rates at increased wastewater temperatures.

Pilot plant studies conducted with 4-ft diameter polystyrene RBC discs by Borchardt et al. (19) on trickling filter effluent also produced a Monod-type prediction of ammonia nitrogen removal rate. Their data, which will also be discussed further in Section 5, could not be segregated into separate curve fits at different temperature levels.

Early literature citations by Antonie (4) suggested that ammonia nitrogen removal followed a first-order kinetic relationship through at least four stages of RBC media. Based on further pilot plant testing at Madison, Wisconsin, and Guelph, Ontario, and correlation with full-scale performance data, Autotrol revised its nitrification design basis in the late 1970's (24). The updated design procedure projects first-order removal (oxidation) of ammonia nitrogen at concentrations in the stage liquid below about 5 mg/l. Above 5 mg/l NH_3-N, removal is claimed to proceed at a maximum zero-order rate consistant with the prevailing wastewater temperature and other environmental factors. Applied to a given RBC system, this design basis assumes that, if soluble BOD_5 is below 15 mg/l, incoming ammonia nitrogen will be oxidized at a constant (zero-order) rate as it passes through succeeding stages down to about 5 mg/l and thereafter at a first-order rate. Autotrol's updated curve for full-scale RBC's (24), plotted in Figure 2-9, exhibits a zero-order removal rate above 5 mg/l NH_3-N of approximately 0.3 lb NH_3-N oxidized/day/1000 sq ft at a wastewater temperature of 55°F.

Studies undertaken at the Canadian Wastewater Technology Centre (60) investigated zero-order, half-order, and first-order kinetic expressions for describing nitrification data developed on a 1.6 ft-diameter polyethylene disc pilot unit. The zero-order model was selected as best fitting the data, with a constant TKN removal rate of 0.22 lb/day/1000 sq ft at TKN concentrations above 4 mg/l.

The literature citations of different kinetic models as best describing the oxidation of ammonia nitrogen in the RBC process are not necessarily inconsistent. As noted in Section 2.4, if S in the Monod expression is much larger than K_s, substrate (in this case ammonia nitrogen) removal will approach a zero-order rate. Conversely, as substrate is removed and S approaches the value of or becomes smaller than K_s, further substrate removal will begin to approximate a first-order rate. The limits at which these transitions occur in a given nitrifying RBC depend on biology, scale, environmental conditions, mass transfer, and other factors.

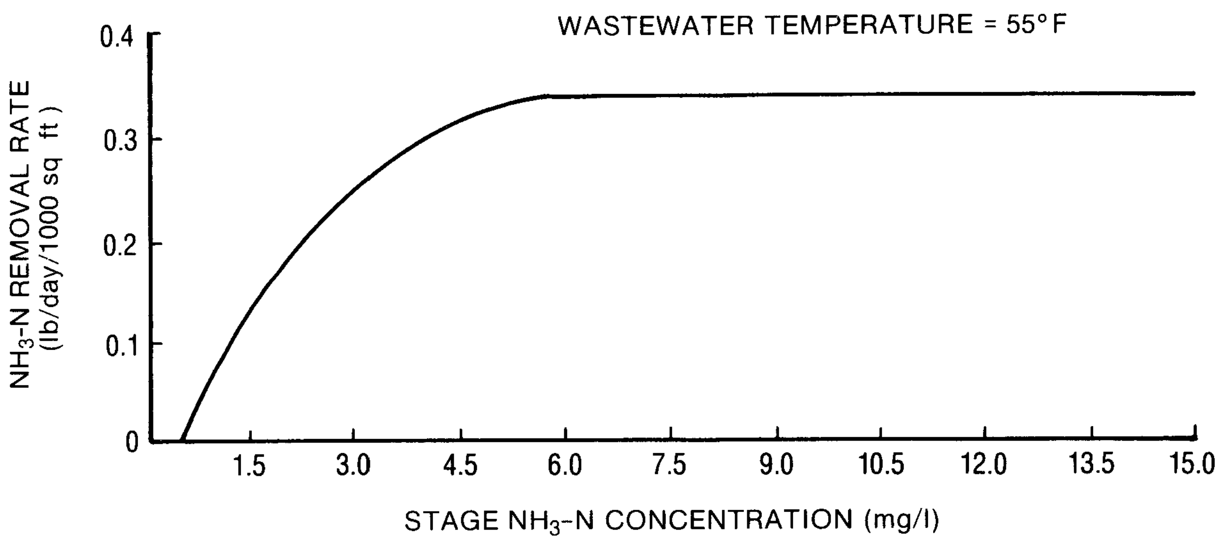


Figure 2-9. Second-generation Autotrol ammonia nitrogen removal rate curve for full-scale RBC's [from Antonie (24)].

2.8.4.3 Influent Nitrogen Composition

RBC nitrification designs are often based on influent ammonia nitrogen concentration rather than influent unfiltered or soluble TKN concentration. For nitrification of biologically treated effluents, this approach is justified and should present no sizing problems. In combined carbon oxidation-nitrification applications, however, such an approach could lead to gross undersizing of the required media surface area in the tail-end nitrification portion of the reactor.

Total unoxidized nitrogen is determined by the TKN procedure. TKN in turn is composed of soluble and particulate fractions. The soluble fraction contains urea and other organic nitrogen compounds as well as the inorganic ammonia nitrogen component.

In raw wastewater, it is not unusual for unfiltered TKN-to-soluble TKN ratios to reach 2.0 or greater. Following primary clarification, the particulate TKN fraction is normally reduced to a few mg/l. At this point in a plant treatment train, it is still possible for the soluble TKN concentration to be much larger than the ammonia nitrogen concentration. This situation occurs when, for whatever reasons, large quantities of urea have not yet hydrolyzed to ammonia nitrogen. Prior hydrolysis depends on a number of factors, including temperature and holdup time in the sewer system. When primary effluent enters a biological reactor, however, the hydrolysis is usually rapidly completed, adding to the ammonia nitrogen load available for nitrification.

Consider the following primary effluent composition data for August 13 and 14, 1975, for the full-scale, six-stage RBC system at Gladstone, Michigan (61):

Parameter (mg/l)	August 13	August 14
Unfiltered TKN	28.0	24.8
Soluble TKN	23.0	21.5
NH_3-N	9.2	17.7
NO_3-N	0.6	0.0

On August 14, the soluble TKN concentration in Gladstone's primary effluent was only 3.8 mg/l higher than the ammonia nitrogen concentration. On the preceding day, however, the difference in these two concentrations was 13.8 mg/l. In this example, the use of primary effluent ammonia nitrogen data alone in establishing required media surface area for RBC nitrification would obviously constitute a dangerous design practice and could result in severe undersizing.

A procedure recommended by Autotrol for designing combined carbon oxidation-nitrification RBC systems is to assume that particulate TKN will pass reasonably unchanged through the process and that all the influent soluble TKN minus some loss for heterotrophic metabolism will be available for nitrification before exiting the reactor. Based on analysis of numerous data sets, Sullivan (6) has suggested using a subtraction factor of 0.10 x soluble BOD_5 removed as an estimate of the amount of nitrogen consumed in heterotrophic metabolism. For separate-stage RBC nitrification, hydrolysis of soluble TKN to ammonia nitrogen will have been essentially completed by the time first-stage effluent enters the RBC reactor. In this case, incoming soluble TKN and ammonia nitrogen concentrations should be approximately the same.

A less empirical approach is to assume that all influent total TKN, excepting a small refractory portion, will become available for metabolism and nitrification in an RBC system through hydrolysis and other enzymatic reactions. Randtke et al. (62) found that soluble organic nitrogen (SON) in the effluent of four full-scale activated sludge plants treating municipal wastewaters averaged 1.5 mg/l. Approximately two-thirds of this amount was determined to be refractory organic materials present in the untreated wastewaters, and one-third was generated biologically during treatment. An approximate protoplasm composition of $C_{106}H_{180}O_{45}N_{16}P_1$, which represents 9.2 percent nitrogen, has been proposed by Barth and Bunch (63). Combining this percentage with a conservative yield factor of 0.6 x soluble BOD_5 removed yields a nitrogen subtraction factor for heterotrophic metabolism of 0.055 x soluble BOD_5 removed. With this approach then, media requirements for RBC nitrification would be based on an equivalent ammonia nitrogen concentration (mg/l) equal to influent total TKN (mg/l) minus 1.0 mg/l refractory SON minus 0.055 x soluble BOD_5 removed (mg/l). Whatever procedure is utilized, it is essential that the equivalent ammonia nitrogen load an RBC sysem is designed to nitrify includes the anticipated unoxidized nitrogen recycle loads from sludge digestion and conditioning processes.

2.8.4.4 Wastewater Temperature

It is universally acknowledged that decreasing wastewater temperature adversely affects the growth rates of nitrifying organisms and their corresponding capabilities for carrying out oxidative reactions. Differences of opinion exist concerning the magnitude of the temperature impact over the temperature range of interest in municipal wastewater treatment.

Downing and coworkers (52)(53) developed the following temperature relationships for the maximum growth rate, $\hat{\mu}_N$, and the half-saturation constant, K_N, of pure cultures of Nitrosomonas:

$$\hat{\mu}_N = 0.47e^{[(0.098(T - 15)]}, \text{ mg/l as N} \quad (2\text{-}12)$$

$$K_N = 10^{(0.051\,T - 1.158)}, \text{ day}^{-1} \quad (2\text{-}13)$$

where T is the wastewater temperature (^oC).

Using a 2-ft diameter RBC pilot plant fed synthetic wastes in a laboratory environment, Borchardt et al. (19) developed a temperature curve that predicts an approximate doubling in the nitrification rate for every 18^{o}F rise in wastewater temperature between 50 and 86^{o}F. Pilot-scale RBC work at Utah State University (23) resulted in a projected value of 1.103 for the nitrification temperature coefficient, θ_N, between 59 and 68^{o}F. Their pilot reactor operating at 41^{o}F produced no nitrification. Mueller et al. (64) chose a θ_N value of 1.10 in calibrating a model developed to represent RBC nitrification.

Murphy and Wilson (1) conducted RBC pilot evaluations of combined carbon oxidation-nitrification using 1.6-ft and 6.6-ft diameter polyethylene media. They established design loading criteria based on influent soluble TKN for an effluent unfiltered TKN goal of 5 mg/l as a function of wastewater temperature. Their design premise assumed an influent total BOD_5-to-soluble TKN ratio of 6. Final recommended loading criteria in lb soluble TKN/day/1000 sq ft ranged from 0.05 at 41^{o}F to 0.08 at 50^{o}F to 0.13 at 59^{o}F to 0.23 at 68^{o}F, or a 4.6-fold increase from the lowest to the highest temperature considered.

Nitrification temperature correction curves developed by four RBC manufacturers, Autotrol, Clow, Lyco, and Manufacturer X, are compared in Figure 2-10 (42). (Published curves were not available for Walker Process and Crane-Cochrane.) The correction factors shown refer to the additional media surface area required to achieve equivalent nitrification efficiency at the indicated temperature as at 55^{o}F. All of the curves are very similar in the 45 to 55^{o}F range. Lyco's recommended correction factor increases precipitously from 45^{o}F down to 42.5^{o}F and is double the recommended Clow and Autotrol corrections at the lower temperature.

None of the manufacturers recommend decreasing the quantity of media surface area provided for nitrification at wastewater temperatures above 55^{o}F. In light of the reported evidence that nitrification rates in pure cultures and pilot-scale RBC systems increase with increasing wastewater temperatures up to 75 to 85^{o}F, the manufacturers' temperature correction curves suggest that above 55^{o}F, full-scale RBC nitrification rates become increasingly dominated by environmental factors other than temperature, effectively masking the temperature effect.

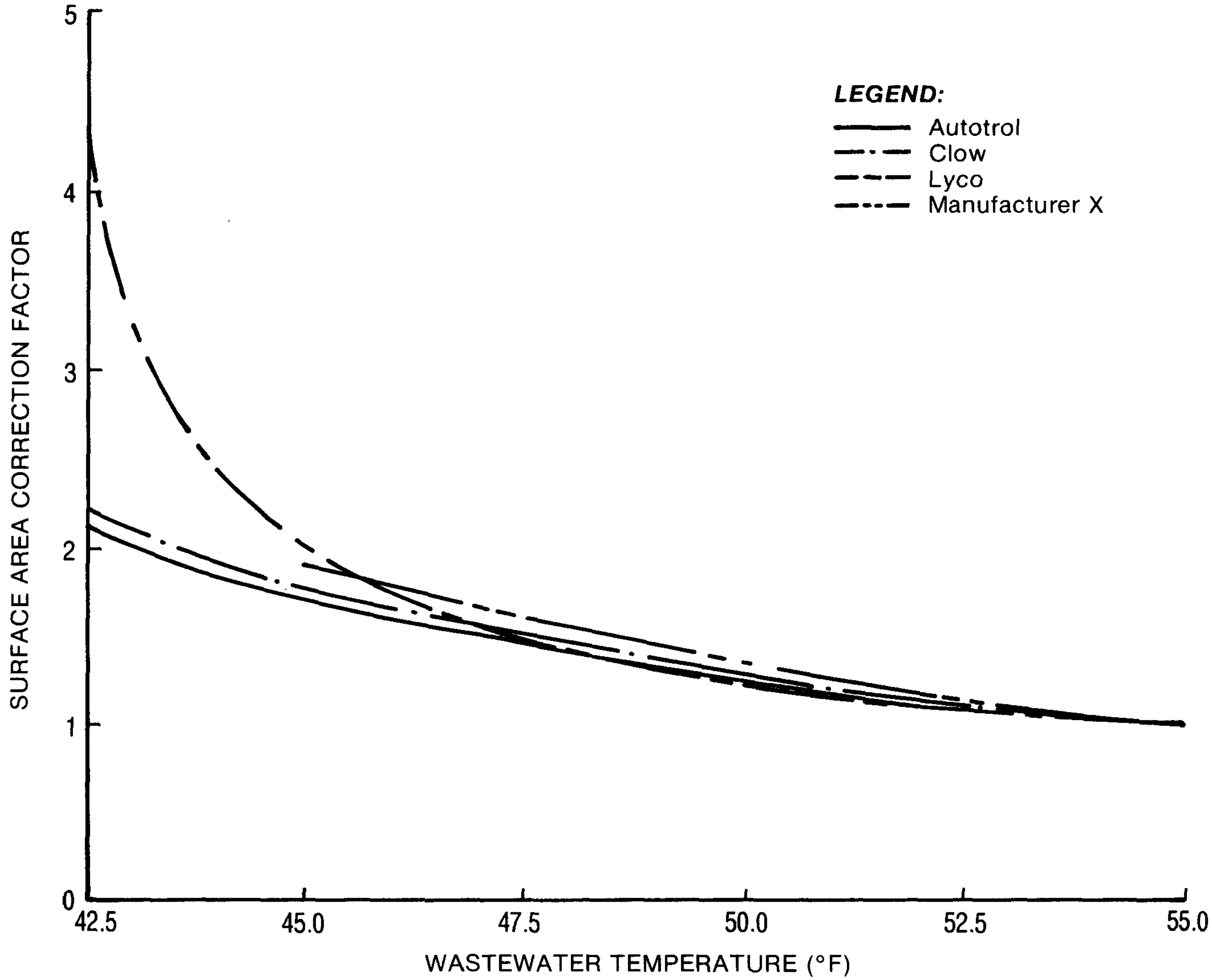


Figure 2-10. Manufacturer temperature correction factors for nitrification [from Roy F. Weston (42)].

2.8.4.5 Dissolved Oxygen

Nitrification is comprised of aerobic reactions that are generally acknowledged as being more sensitive to DO concentration than heterotrophic reactions. A minimum desired DO level of 2 mg/l is often quoted. Cases can be found in the literature, however, where only 40 to 90 percent of the maximum nitrification rate was achieved at 2 mg/l DO (65)(66)(67).

The Nitrogen Control Process Design Manual (45) suggests that the effect of DO on the growth rate (day^{-1}) of Nitrosomonas, μ_N can be represented by the following Monod-type expression, if it is assumed that DO is a growth-limiting substrate:

$$\mu_N = \hat{\mu}_N \left(\frac{DO}{K_{O_2} + DO} \right) \qquad (2\text{-}14)$$

where K_{O_2} is the half-saturation constant for oxygen (mg/l). K_{O_2} values ranging from 0.15 mg/l at 59°F (68) to 2.0 mg/l at 68°F (69) have been proposed. A commonly-used value developed by the British (65) is 1.3 mg/l (temperature unspecified). Based on Equation 2-14 and an assumed K_{O_2} of 1.3 mg/l, a DO level of at least 4 mg/l would have to be maintained to achieve 75 percent of the maximum growth rate of Nitrosomonas.

Borchardt et al. (19) reporting on six-stage, 4-ft diameter RBC nitrification of trickling filter effluent found that a DO level of 3.5 mg/l was necessary in the first three stages to ensure no retardation in oxygen uptake rates. Mass removal rates of ammonia nitrogen in the last three stages of a six-stage, full-scale U.S. Army RBC installation (70) were observed to average 50 percent higher in January (55°F) at stage bulk liquid DO concentrations of 3.5 to 4.8 mg/l than in August (79°F) at DO's of 1.3 to 2.2 mg/l, although possible low pH inhibition of nitrification in both months weakens the case for a direct comparison of removal based on DO levels alone.

If low bulk liquid DO levels are encountered in the nitrification stages of an RBC, transient intrusion of increased levels of soluble BOD into those stages should be investigated as a contributing cause. This situation is more likely to be encountered in combined carbon oxidation-nitrification RBC systems than in separate-stage nitrification reactors.

Decreased nitrification rates in stages experiencing modest organic influx could be due as much or more to inadequate DO in the stage bulk liquid than to nitrifier competition from heterotrophic growth. In these cases, provisions for correcting the DO deficiency on a temporary basis by increasing media rotational speed or providing supplemental air may represent a viable solution. Hydrogen peroxide, while capable of increasing DO, tends to be toxic to nitrifiers and should not be added to nitrifying RBC stages even on a temporary basis. Air drive RBC units would appear to offer a means of eliminating or greatly reducing the potential for DO deficiencies in nitrifying RBC stages. Since air drives are normally rotated at only 65 to 75 percent of the standard 1.6-rpm angular velocity of mechanical drives, however, the beneficial effects of the oxygen in the compressed air are largely offset by lower media oxygenation capacity (6).

If an RBC nitrification system is sized to produce low effluent ammonia nitrogen residuals, i.e., 2 mg/l or less, the increase in DO concentration at the exit end of the train will normally become pronounced. Effluent DO's for the six-stage Gladstone, Michigan, municipal plant routinely reach 6 to 8 mg/l with corresponding ammonia nitrogen concentrations of 1 to 3 mg/l (71).

High effluent-end DO concentrations combined with very low levels of soluble organic material can reportedly lead to deterioration of nitrification rates through proliferation of higher life forms that ingest nitrifying microorganisms. Pilot studies conducted on separate-stage, 10.5-ft diameter nitrification units for the City of Indianapolis (20) correlated reduced nitrification efficiencies with large microscopically-observed quantities of rotifiers, nematodes, and other bacterial predators. A 5- to 8-percent flow spike of primary effluent to the lead RBC stage retarded predator activity, and ammonia nitrogen removal rates increased an average 10 percent for the 10 days after the spike.

To discourage selective predation of nitrifying bacteria, Sullivan (6) recommends maintaining stage bulk liquid DO concentrations of no more than 3.5 mg/l and preventing soluble BOD_5 from dropping below 6 to 8 mg/l in the polishing stages of an RBC nitrification train. Incorporating operations flexibility in the design of an RBC facility in the form of variable-speed drives, a supplemental air system, and/or multiple, individually-valved feed points to the RBC reactor will enable the operator to respond to transient DO and predator conditions that can negatively impact nitrification efficiency.

2.8.4.6 Alkalinity and pH

Nitrification is an acid-producing biochemical reaction. Approximately 7.1 mg of calcium carbonate alkalinity are theoretically destroyed per mg of ammonia nitrogen oxidized. Depending on initial alkalinity and unoxidized nitrogen concentrations, the process of nitrification can potentially reduce wastewater alkalinity to the point where pH will drop to 6.5 and even to 6.0 or less.

A strong relationship between pH and nitrification rate is generally acknowledged. Optimal pH values found in the literature range from 7.0 to 9.0 (50), with nitrification efficiency falling off dramatically as pH decreases form 7.0 to 6.0 in unacclimated systems. Downing and Knowles (72) developed the following expression relating Nitrosomonas growth rate to pH values up to 7.2 for combined carbon oxidation-nitrification systems:

$$\mu_N = \hat{\mu}_N [1 - 0.833 (7.2 - pH)] \qquad (2\text{-}15)$$

Downing and Knowles assumed the growth rate to be constant in the pH range of 7.2 to 8.0.

Borchardt et al. (19) examined the effect of pH on RBC nitrification at eleven different alkalinity levels using a 2-ft diameter polystyrene pilot unit and uniform influent ammonia nitrogen concentrations of 20 mg/l. Short undefined acclimation periods were employed at each alkalinity level. Their results indicated a constant nitrification rate between pH 7.1 and pH 8.6, 25 percent of this constant rate at pH 6.5, and zero nitrification at pH 6.0.

A comprehensive evaluation of pH and alkalinity effects on RBC nitrification was recently completed by Stratta and Long (50). Four single-stage, 19.7-in. diameter pilot systems were operated in parallel using high-rate trickling filter clarified effluent as feed. Two long-term (10-wk) experimental phases were conducted sequentially to investigate nitrification first at pH levels of 6.3 to 7.5 and second at pH levels of 7.6 to 8.8. In both phases, the experiments were begun with clean media on day 1.

Stratta and Long's work demonstrated increasing ammonia nitrogen oxidation rates with increasing pH up to pH 8.5 as shown in Figure 2-11. The rate at pH 8.8 decreased slightly, averaging 94 percent of the maximum rate at pH 8.5. The rates presented in the figure are for the second 5-wk period of each phase after the units had reached equilibrium.

Stratta and Long's pilot RBC units operating at lower pH values developed nitrification rates comparable to those of the higher pH units during the startup phase of each experiment. Nitrification comparability ceased after approximately 35 days of operation, with deterioration of nitrification performance to lower equilibrium rates for the lower pH units. A possible explanation offered by the investigators for this observed phenomenon was the gradual development of secondary predator populations in the lower pH systems.

Long-term pH reversion experiments were conducted by Stratta and Long on RBC pilot systems acclimated to pH 8.0 and pH 8.8. Alkaline addition was terminated so that each system began operating at the control pH level of 7.5. A total of 19 days was required for the pH 8.8 unit to completely revert to normal pH 7.5 nitrification efficiency, while the pH 8.0 unit reverted in 1 wk.

Snails migrating into Stratta and Long's RBC pilot systems along with the trickling filter effluent feed inhabited the trough walls of those units with a pH of 8.0 or less. They were not evident on the trough walls of the pH 8.5 and pH 8.8 units. The snails at no time took up residence on the media surfaces or in the attached biofilm.

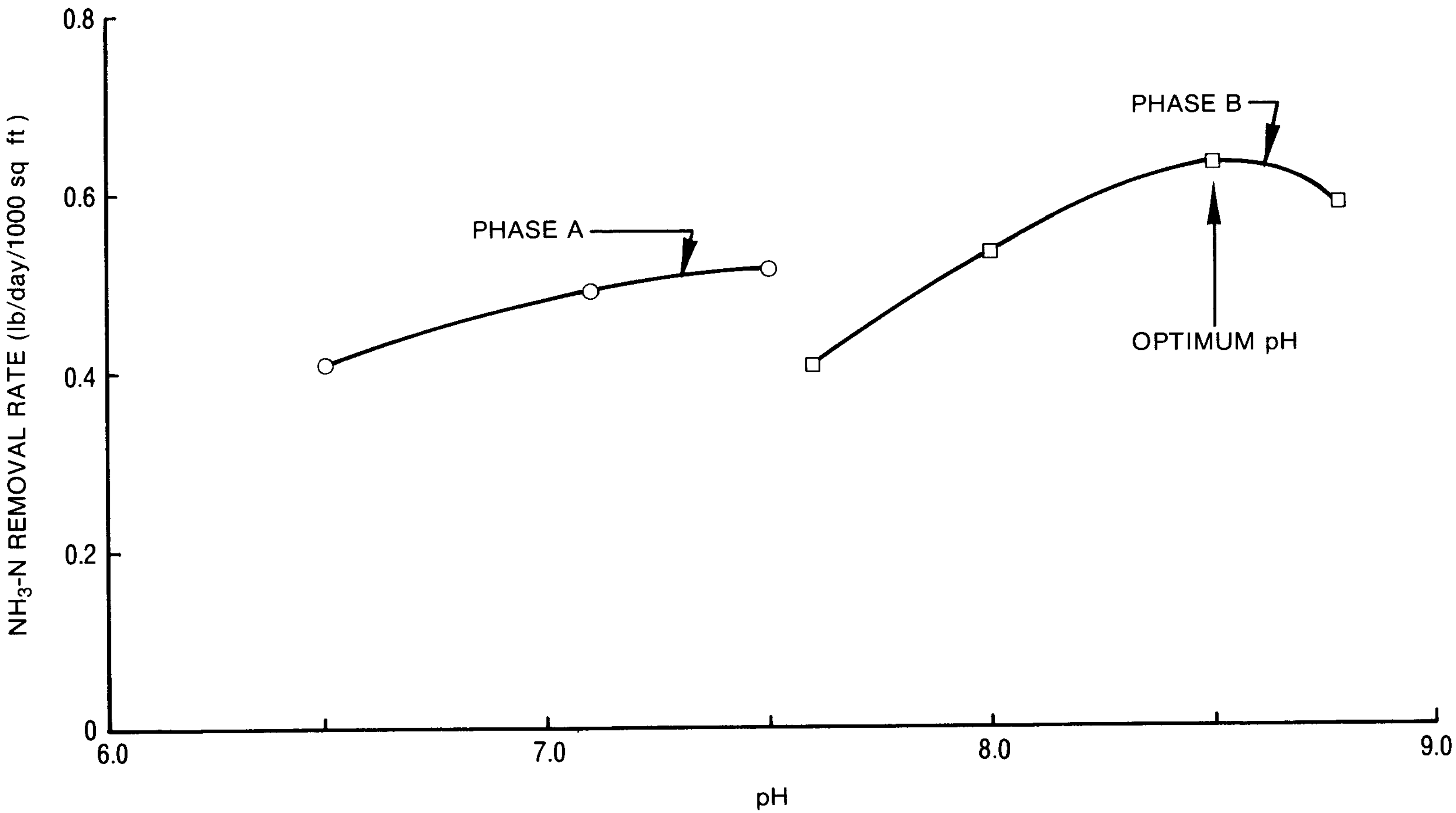


Figure 2-11. Effect of pH on RBC nitrification rates.

Stratta and Long also conducted parallel nitrification enhancement investigations utilizing different alkaline chemicals to adjust pH in four two-stage RBC pilot units. Sodium hydroxide (NaOH), sodium carbonate (soda ash, Na_2CO_3), and calcium hydroxide (lime, $Ca(OH)_2$) were added to the first stage of three of the units to maintain pH in those stages at the previously determined optimum level of 8.5. Sodium bicarbonate ($NaHCO_3$) was dosed to maintain first-stage pH of the fourth unit at 7.5. The results of this work are summarized in Table 2-4.

The data in Table 2-4 exhibit remarkably similar ammonia nitrogen removal rates for the three chemicals (sodium hydroxide, soda ash, and lime) in which first-stage pH was maintained at 8.4 to 8.5. These rates were approximately 19 percent higher than that of the control unit. Second-stage alkalinity destruction varied from 14 percent less to 11 percent more than the theoretical requirement of 7.1 mg $CaCO_3$/mg NH_3-N oxidized. All of the chemically-dosed RBC pilot plants except the lime unit produced only minimal increases in effluent suspended solids of 1 to 3 mg/l. Effluent suspended solids in the lime-dosed unit, however, increased 20 mg/l.

The potential for enhancement of RBC nitrification rates at elevated pH's (8.0 to 8.8) demonstrated by Stratta and Long (50) on pilot scale systems has yet to be duplicated with full-scale units. Albert (73) attempted to confirm their results at a field-scale U.S. Army RBC plant. Soda ash was dosed to the third stage of a six-stage, combined carbon oxidation-nitrification train, i.e., at that point in the train where the onset of nitrification was routinely observed. Although the target pH at the dose point was the optimum 8.5 pH value noted by Stratta and Long, actual pH varied from 8.1 to 9.3 because automatic pH control had not been provided. A side-by-side performance comparison with an undosed control train showed no overall enhancement of nitrification rates in the dosed train, only a slight alternation in the interstage

TABLE 2-4. ALKALINE ENHANCEMENT RBC NITRIFICATION DATA FROM STRATTA AND LONG (50)

Alkaline Chemical	First-Stage pH*	Second-Stage pH	NH_3-N Removed Overall (lb/day/1000 sq ft)	Alkalinity Destroyed in Second State (mg $CaCO_3$/mg NH_3-N)
NaOH	8.5	7.9	0.516	6.1
Na_2CO_3	8.4	8.0	0.520	7.9
$Ca(OH)_2$	8.5	7.9	0.522	7.0
$NaHCO_3$	7.5	7.7	0.492	7.7
Control	7.0	6.9	0.438	7.2

*Influent to first stage maintained at pH 6.5 and 150 mg/l $CaCO_3$ alkalinity.

ammonia nitrogen removal pattern. The investigator suggested the lack of observed improvement was probably due to the wide pH fluctuations experienced, which preprevented constant-pH acclimation of the nitrifying population.

As discussed in Section 2.8.5.2, other factors such as oxygen transfer and wastewater temperature may exert sufficient impact on full-scale RBC nitrification to cancel or substantially damp any potentially beneficial effects of pH optimization. Full-scale pH enchancement of RBC nitrification is a worthy subject of further research, however.

2.8.4.7 Inhibition

Research data specific to nitrification inhibition in RBC's are generally unavailable in the literature. It has been established that certain organic compounds and heavy metals are toxic to unacclimated cultures of nitrifying organisms (46)(74)(75)(76). Allyl-thiourea, for example, is an organic compound frequently used to inhibit nitrification in the BOD test. Heavy metals that have been implicated in nitrifier inhibition or toxicity include chromium, copper, mercury, nickel, silver, and zinc, among others. Where industrial wastes containing very high levels of ammonia or nitrite nitrogen are discharged to municipal sewer systems as slug loads, temporary nitrifier toxicity can result if the concentration increase for either nitrogen form is sufficiently large (77).

Sawyer (78) has reported that 10 to 20 mg/l of some heavy metals can be tolerated by nitrifiers at pH values of 7.5 to 8.0 where ionic disassociation is small. Other metals that precipitate as hydroxides cause relatively little inhibition as long as they remain insoluble but become very toxic if dissolved, such as can happen with falling pH. Silver has been found to be toxic to plastic media trickling filter nitrification of secondary effluent at concentrations as low as 2 μg/l (79).

Equally important to the type and concentration of potential nitrification inhibiting substances encountered is the variability with which they enter the treatment system. Biological acclimation enables nitrifiers to adapt to higher concentrations of these substances when present at reasonably consistent levels than can be tolerated in slug loadings.

When lower-than-anticipated RBC nitrification rates (or cessation of nitrification altogether) are experienced, conventional environmental impact factors such as wastewater temperature, DO, and pH; nuisance growths; and organic and ammonia nitrogen loadings should be investigated first. If these factors can be ruled out as contributory agents to the problem, a comprehensive wastewater characterization study is usually the next step. The compounds and metals included in a characterization screening should be predicated on the type and magnitude of industrial and commercial wastes known or suspected to be entering the municipal treatment facility.

2.8.5 Interdependency of Factors Affecting Nitrification

2.8.5.1 Combined Kinetic Expression

Kinetic factors affecting nitrifier growth and nitrification rate were discussed in Section 2.8.4. In the absence of inhibitory or toxic wastewater components, the major factors are ammonia nitrogen concentration, wastewater temperature, DO, and pH. A general expression was presented in Equation 2-5 indicating the interdependency of these kinetic parameters on unit substrate (nitrogen ammonia) removal rate. A similar combined Monod expression has been proposed (45) to relate Nitrosomonas growth rate to the same factors:

$$\mu_N = \hat{\mu}_N \left(\frac{N}{K_N + N}\right)\left(\frac{DO}{K_{O_2} + DO}\right)(a\ pH^b) \qquad (2\text{-}16)$$

where N is the ammonia nitrogen concentration (mg/l).

Substituting Equation 2-12 as an estimate of the effect of temperature on μ_N, Equation 2-13 for K_N, the British-developed value of 1.3 mg/l (64) for K_{O_2}, and Equation 2-15 for the general pH effect term yields the following specific equation valid for pH $\leq$ 7.2 and wastewater temperatures between 8 and 30°C (45):

$$\mu_N = 0.47\ [e^{0.098(T - 15)}] \left[\frac{N}{10^{(0.051\ T - 1.158)} + N}\right] \cdot \left[\frac{DO}{1.3 + DO}\right] [1 - 0.833(7.2 - pH)] \qquad (2\text{-}17)$$

The above equations indicate that if all the kinetic terms considered approach their maximum values, i.e., if N is large in comparison to K_N, if DO is substantially larger than 1.3 mg/l (say 4 to 6 mg/l), and if pH is in the range of 7.0 to 7.2, μ_N will approach that $\hat{\mu}_N$ value dictated by wastewater temperature. (Downing and coworkers (52)(53) have estimated $\hat{\mu}_N$ to be 0.47 day^{-1} at 15°C (59°F).) Conversely, if any one factor or parameter becomes limiting, even if all the rest are non-limiting, μ_N and the attainable nitrification rate will be much lower, perhaps even zero if the limiting condition is severe enough.

2.8.5.2 Comparison of Pilot- and Full-Scale RBC Nitrification Rates

As will be shown in Section 5, peak demonstrated nitrification rates for full-scale RBC's generally fall in the range of 0.3 to 0.35 lb NH_3-N oxidized/day/1000 sq ft media surface area. The updated Autotrol design procedure is based on a maximum zero-order oxidation rate of approximately 0.3 lb NH_3-N/day/1000 sq ft at ammonia nitrogen concentrations of 5 mg/l or higher in the bulk liquid as illustrated previously in Figure 2-9 (24).

Published pilot-scale RBC data typically exhibit maximum nitrification rates 1.5 to 2.5 times higher than full-scale peak nitrification rates. Rates as high as 0.74 to 0.78 lb NH_3-N/day/1000 sq ft were observed by Borchardt et al. (19) on a 4-ft diameter RBC unit at temperatures of 50 to 65^{o}F. Pano et al. (23) achieved rates of 0.45 to 0.68 lb NH_3-N/day/1000 sq ft on 15-in. diameter pilot discs in the temperature range of 59 to 68^{o}F. Stratta and Long (50) utilized pH enhancement to increase nitrification rates from a control plateau ($7.0 < pH < 7.2$) of 0.44 to 0.48 lb NH_3-N/day/1000 sq ft to levels ($8.0 < pH < 8.8$) of 0.52 to 0.62 lb NH_3-N/day/1000 sq ft on 19.7-in. diameter pilot RBC's. A maximum zero-order removal rate of 0.50 lb NH_3-N/day/1000 sq ft was attained at 65^{o}F on a 19.7-in. diameter unit at Guelph, Ontario (22).

Explanations of the higher nitrification rates observed in pilot-scale RBC units compared to full-scale systems are related to mass transfer considerations and the limitations of each system. Mass transfer effects are not directly addressed by expressions such as Equation 2-16, but they can exercise a dominant influence on observed nitrification rates. As discussed in Section 2.6, the higher rotational velocities universally employed with pilot RBC's decrease the available time for ammonia nitrogen depletion in the atmospheric portion of the cycle and DO depletion in the submerged portion of the cycle. Decreased time of depletion and/or increased levels of oxygen and substrate in the biofilm permit the kinetic terms considered in Equation 2-16 to remain at higher values throughout the rotational cycle.

As indicated in Section 2.7.2.2, COD balance studies conducted by Scheible and Novak (39) suggested a peak overall oxygen transfer rate of 1.4 to 1.5 lb O_2/day/1000 sq ft for 12-ft diameter, mechanically driven RBC's. If a peak rate of 1.5 lb O_2/day/1000 sq ft is assumed, the maximum potential nitrification rate for 12-ft diameter media is estimated as:

$$\frac{1.5 \text{ lb } O_2\text{/day/1000 sq ft}}{4.6 \text{ lb } O_2\text{/lb } NH_3\text{-N}} = 0.33 \text{ lb } NH_3\text{-N/day/1000 sq ft}$$

The above estimate corresponds well to documented full-scale RBC maximum nitrification rates (refer to Section 5) and Autotrol's predicted maximum zero-order ammonia nitrogen removal rate for full-scale units. In contrast, oxygen transfer rates necessary to achieve typical pilot-scale nitrification rates documented herein range from 2.2 to 3.7 lb O_2/day/1000 sq ft. Several factors that contribute to greater oxygen transfer potential in RBC pilot systems were described in Section 2.6.

Nitrification rates have been achieved in some stages of full-scale RBC systems at or near the consensus maximum rate of 0.3 lb NH_3-N/day/1000 sq ft with bulk liquid DO's of 2 to 4 mg/l (61). The presence of measurable bulk liquid DO when a stage's nitrification rate is presumably being controlled by oxygen transfer appears to be contradictory. Although definitive literature on this subject is lacking, the fact that only 2 to 4 percent of the assumed maximum oxygen transfer rate (1.5 lb/O_2/day/1000 sq ft) is required to increase bulk liquid DO from 0 to 4 mg/l across an RBC system at typical hydraulic loading rates may offer a partial explanation.

Oxygen transfer limitations and substrate depletion rates may also figure prominently in the discrepancy of observed temperature effects between full- and pilot-scale RBC equipment. As illustrated previously in Figure 2-10, the manufacturers do not recommend the use of a wastewater temperature correction factor above 55°F. The validity of this recommendation is supported by field data presented in Section 5. Borchardt et al. (19), on the other hand, measured a 10-percent increase in nitrification rate at temperatures of 54 to 67°F compared to temperatures of 45 to 55°F using 4-ft diameter polystyrene units. Pano et al. (23) achieved a 50-percent higher rate at 68°F than at 59°F on 15-in. diameter pilot systems.

As indicated in the aforegoing discussion, several kinetic parameters strongly influence RBC nitrification. The designer must have an appreciation for the interdependency of these parameters to intelligently size RBC nitrification systems. If pilot-generated data are to be used as a basis for full-scale design, the designer will either have to establish or accept a previously-established empirical scale-up technique or attempt calibration and utilization of one of several available RBC deterministic models.

2.9 Denitrification

2.9.1 Background

When the DO level is near or at zero, many heterotrophic microorganisms are able to use nitrate nitrogen as an alternate electron acceptor for dissimilatory nitrate reduction to nitrogen gas. This phenomenon has been widely used in wastewater treatment systems for nitrogen removal. Unoxidized nitrogen must first be biologically converted to nitrate nitrogen in an aerobic environment. Denitrification can be accomplished in separate-stage RBC systems where carbonaceous oxidation and nitrification occur in the lead stage(s) of the RBC process train and a carbon source, commonly methanol, is added to provide the energy for microbial denitrification in the last (anoxic) stage. This approach is illustrated in Figure 2-12. When this approach is employed, it may be necessary to add a terminal aerated RBC stage to the system to oxidize any residual methanol not utilized for denitrification.

RBC systems can also be staged to achieve denitrification as indicated in Figure 2-13. In this case, the anoxic unit is the first stage of the RBC train and the organic carbon naturally present in the wastewater is used for nitrate reduction; nitrate nitrogen must be introduced to this stage by recirculation of nitrified wastewater from the downstream stages. This technique is well known for activated sludge systems, e.g., the Bardenpho process, but has not been utilized thus far in any full-scale municipal RBC installations in the United States. According to the Autotrol patent for this denitrification alternative (80), the required recirculation rate is from 100 to 300 percent of the flow rate entering the plant and as much as 75 percent of the recirculated nitrate nitrogen can be reduced to nitrogen gas. Since the stoichiometric quantity of alkalinity produced/mg NO_3-N reduced to nitrogen gas is 3.57 mg as $CaCO_3$, the recirculation approach is advantageous where pH adjustment and/or control are required to promote efficient nitrification.

As no DO is desired in the denitrification reaction, RBC media should be completely submerged in the wastewater for denitrification applications. The submerged media are mechanically driven at a rotational velocity of about 1.6 rpm according to the current design procedure (15). Because RBC denitrification is an emerging technology with only one U.S. full-scale municipal facility at Orlando, Florida (81), in operation as of September 1982, the mechanical reliability and ramifications of submerged media and shaft operation are unknown.

2.9.2 Kinetics

As noted by Harremoes and Riemer (82), denitrification is for all practical purposes a zero-order reaction with respect to the nitrate nitrogen concentration. The Michelis-Menten constant, K_s, is on the order of 0.1 mg/l. The change in reaction rate to first order at low concentrations can be ignored.

If the biofilm on the surface of the RBC media is fully penetrated by organic carbon, e.g., methanol, and nitrate, the reaction will follow zero-order removal and be independent of the bulk liquid concentration. In this case, the shear forces caused by rotation of the media are sufficient to prevent the development of a biofilm that is thick enough to allow depletion of nitrate anywhere within the film. If the biofilm is not fully penetrated, the reaction becomes half order with respect to the bulk liquid concentration (14). Based on the observations of Jeris et al. (83) with a denitrifying fluidized bed, biofilms do not appear to be particularly fragile in denitrification systems; these observations are contrary to the findings of Sullivan (6), however, for denitrification in RBC systems.

Total methanol consumption for denitrification has been calculated by Christensen and Harremoes (84) as 2.42 mg/mg NO_3-N reduced. Methanol is also required to reduce any initial DO present in the incoming wastewater. A commonly-used design value for the required methanol dosage is 3 mg/mg NO_3-N to be reduced.

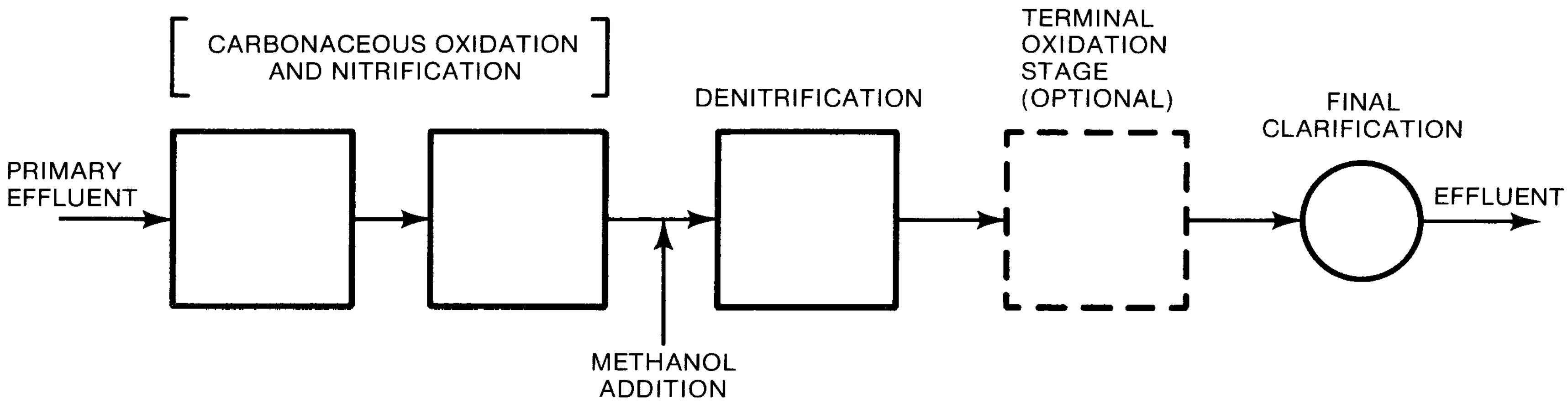


Figure 2-12. RBC process configuration for denitrification using methanol addition.

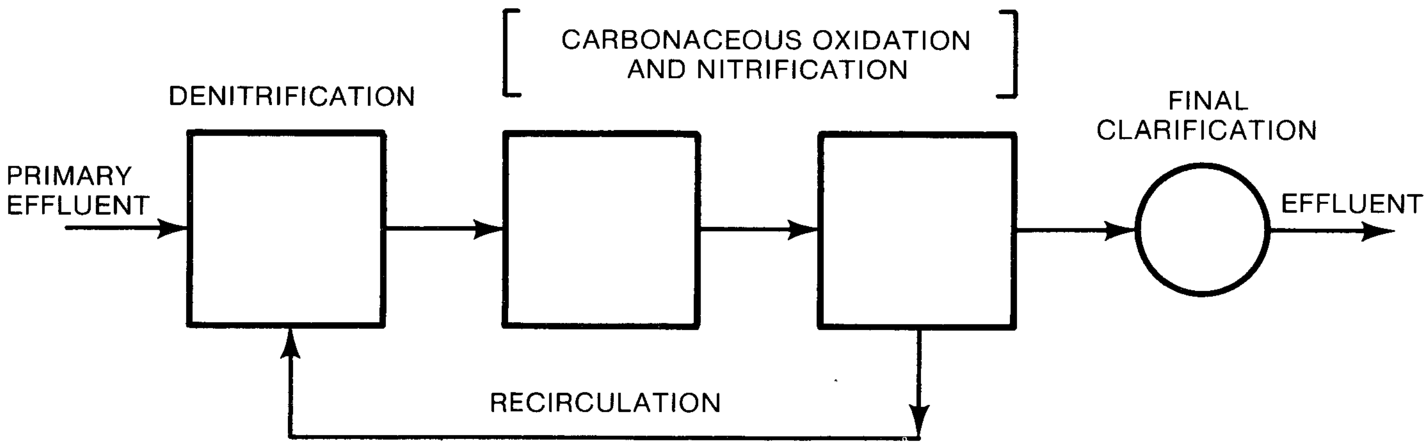


Figure 2-13. RBC process configuration for denitrification using primary effluent as the carbon source.

Williamson and McCarty (12) employed a stoichiometric requirement of 2.5 mg methanol/mg NO_3-N in conjunction with a ratio of methanol-to-nitrate diffusion coefficients of 2.0 inside the biofilm to predict that methanol would have to be supplied in concentrations approximately five times as large as the nitrate nitrogen concentration if methanol is not to be flux limiting in fixed film systems. They concluded, therefore, that denitrification in a biofilm reactor will be flux limited by methanol and not nitrate when methanol is supplied in stoichiometric quantities. This is an interesting conclusion since the kinetic analyses of fixed film systems frequently ignore the methanol level, provided it is present in excess of the stoichiometric requirement.

2.9.3 Previous Studies and Empirical Design Formulations

The Autotrol design manual (15) presents a series of denitrification design curves showing predicted effluent nitrate nitrogen concentrations for various influent concentrations and hydraulic loading rates. According to Sullivan (6), these curves were developed from observations at several sites. An analysis of these curves indicates that the claimed denitrification rate is independent of bulk liquid nitrate nitrogen down to a concentration of 1 mg/l and that the denitrification rate for 55^{o}F is approximately 0.9 lb NO_3-N/day/1000 sq ft. A companion design curve (15) provides wastewater temperature correction factors applicable over the range of 45 to 65^{o}F, with the correction factor at 65^{o}F about three times that for 45^{o}F, i.e., one-third the media surface area is required at 65^{o}F for a given hydraulic loading.

The approach utilized by Autotrol is consistent with the statement of Murphy et al. (60) that their studies indicated that denitrification in the presence of an adequate organic carbon source was independent of the bulk liquid nitrate nitrogen concentration. However, since the data on which this conclusion was based were not presented, it is impossible to evaluate Murphy et al.' results. A four-stage, 19.7-in., submerged RBC pilot unit rotated at 13 rpm was utilized in their work. The observed denitrification rate at 55^{o}F was approximately 0.85 lb NO_3-N/day/1000 sq ft. This rate is roughly double that reported for submerged, high-porosity media denitrification systems (45).

In contrast to the conclusion of Murphy et al. (60) and the design approach utilized by Autotrol (15), the studies reported by Blanc et al. (85) using totally submerged 2-ft diameter discs rotated at 3-1/8 rpm with methanol addition to the nitrified effluent feed at the Marlborough, Massachusetts Easterly treatment plant indicated a strong dependency of denitrification rate on nitrate nitrogen concentration in the bulk liquid in the 0 to 6 mg/l range (Figure 2-14). A strong dependence of denitrification rate on nitrate nitrogen concentration in the bulk liquid was also reported by Harremoes and Riemer (82) when nitrified wastewater receiving 3 mg methanol/mg NO_3-N was fed to downflow filters. The observed removal rate in any filter section was a function of bulk liquid concentration below about 30 mg/l NO_3-N. The analysis by Rittmann and McCarty (86) of the denitrification results reported by Jeris et al. (83) with expanded bed operation also noted a continual decline in

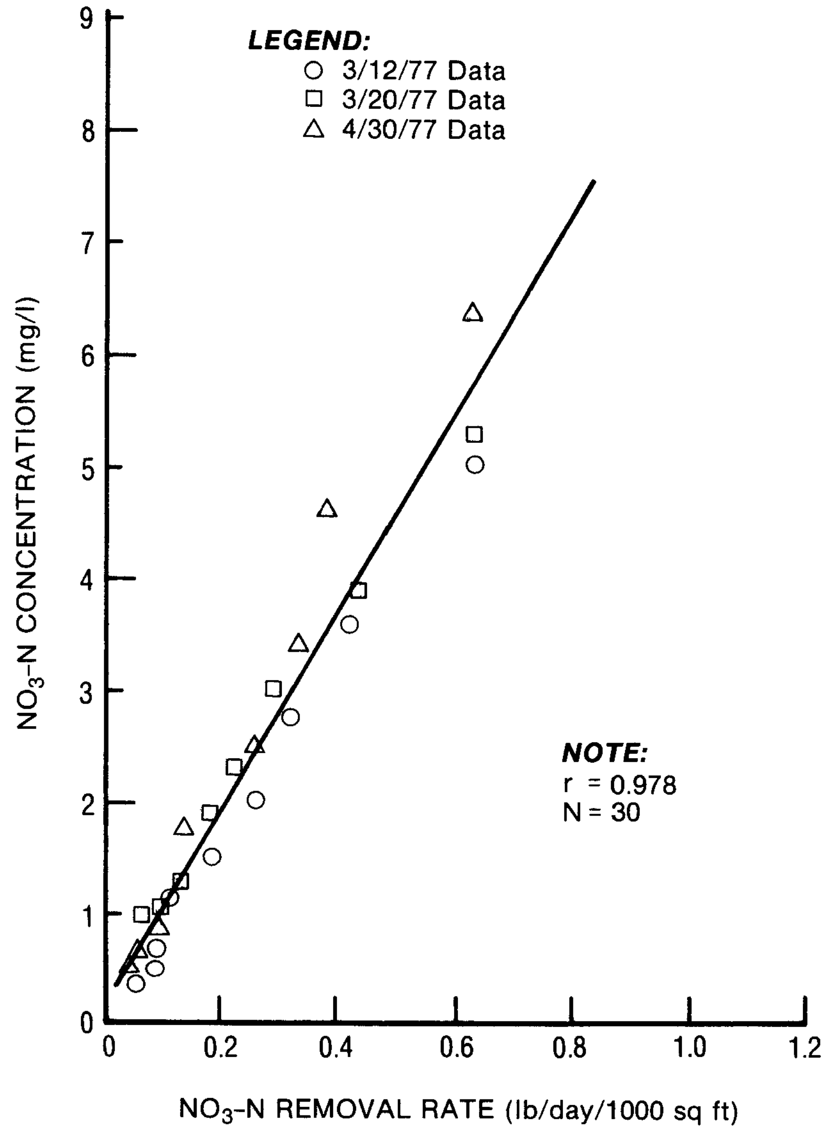


Figure 2-14. RBC denitrification rate for no-flow conditions as a function of bulk liquid nitrate nitrogen concentration [adapted from Blanc et al. (85)].

methanol utilization rate with distance up the column.

In view of the extremely limited data available, it is impossible to make firm conclusions about the general appropriateness of assuming that RBC denitrification rates are independent of nitrate nitrogen concentration down to 1 mg/l in the bulk liquid as currently proposed (15)(60). It is clear that denitrification is not independent of bulk liquid nitrate nitrogen concentration for other fixed film systems. Mass transfer considerations and the results of Blanc et al. (85) suggest that additional RBC denitrification studies are required to define design loading parameters that can be used with confidence, particularly for any configuration where nitrate nitrogen levels will be present in concentrations less than 6 mg/l in the denitrification section of the RBC reactor.

2.10 Secondary Clarification

The concentration of suspended solids leaving the last stage of an RBC train treating municipal wastewater will normally be less than 300 mg/l if primary clarification is not provided and less than 200 mg/l where primaries are used. The settling characteristics of RBC solids during secondary clarification, therefore, will essentially be those of a dilute suspension with zone or compression settling confined to the clarifier bottom. Settling analyses for this type of settling were described by Camp (87). Whenever a nitrified effluent is produced, settled solids should not be allowed to accumulate in the final clarifier for any substantial period (primarily depending on temperature) to avoid solids resuspension and flotation from denitrification reactions.

Studies conducted by Scheible and Novak (39) at the Edgewater, New Jersey RBC facility indicated that peak surface overflow rates had to be limited to 550 to 650 gpd/sq ft to achieve less than 30 mg/l of suspended solids in the final effluent. Based on pilot plant studies, Srinivasaraghavan et al. (88) recommended an average design overflow rate of 740 gpd/sq ft for the full-scale Pinners Point RBC plant. Murphy and Wilson (1) recommend surface overflow rates less than 600 gpd/sq ft to maximize solids removal. According to Smith et al. (89), the recommended range of secondary clarifier average overflow rates for trickling filter upgrading applications is 500 to 800 gpd/sq ft, with 800 applying if the effluent suspended solids objective is 30 mg/l and 500 gpd/sq ft if the goal is 15 mg/l. These ranges are the same as recommended by Autotrol (15). Clow (16) recommends 800 gpd/sq ft for a 30/30 effluent and not more than 500 gpd/sq ft for an effluent of 10 mg/l effluent suspended solids. DeCarlo (90) recommends that peak hydraulic loading rates be limited to 1000 to 1200 gpd/sq ft.

Polymer addition is an effective technique for improving solids capture in secondary clarifiers. Polymer storage, mixing, and feed equipment can be incorporated as rather inexpensive insurance in the design of an RBC facility or it can be installed later if a chronic effluent clarity problem arises.

2.11 Sludge Production

Sludge production in RBC systems is sometimes estimated by subtracting the influent suspended solids to the RBC unit from the suspended solids leaving the last stage and then relating the net solids gain to the amount of soluble BOD_5 removed. This approach tends to estimate small values for sludge production.

As shown previously in Table 2-2, the SRT of RBC biomass in the exterior biofilm layers, which is in pseudo equilibrium with the bulk liquid, is a function of the BOD_5 removal rate, i.e., the loading the biomass is seeing. Since the organisms that grow in an RBC system are the same types that populate activated sludge, RBC sludge production will depend on the loading to each stage, the average residence time of the biofilm on a stage, and the fate of suspended material that passes from stage to stage in multistage units, i.e., whether it can reattach to the RBC surface in subsequent stages, thus allowing further time for degradation. The above sludge age concept for predicting sludge production from RBC systems has also been applied to trickling filter systems (91).

2.12 References

1. Murphy, K. L. and R. W. Wilson. Pilot Plant Studies of Rotating Biological Contactors Treating Municipal Wastewater. Report SCAT-2, Environment Canada, Ottawa, Ontario, Prepared for Canada Mortgage and Housing Corporation, July 1980.

2. Hoag, G. E., W. D. Widmer, and W. H. Hovey. Microfauna and RBC Performance: Laboratory and Full-Scale Systems. In: Proceedings of the 1st National Symposium/Workshop on Rotating Biological Contactor Technology, Vol. I, EPA-600/9-80-046a, NTIS PB81-124539, June 1980. pp. 167-187.

3. Rutgers University, Department of Environmental Sciences. Rotating Biological Disk Wastewater Treatment Process - Pilot Plant Evaluation. Final report for Grant No. 17010 EBM, USEPA, Municipal Environmental Research Laboratory, Cincinnati, Ohio, August 1972.

4. Antonie, R. L. Fixed Biological Surfaces - Wastewater Treatment: The Rotating Biological Contactor. CRC Press, Cleveland, Ohio, 1976.

5. Ingram, W. M. Snails Associated with Sewage Treatment. Sewage and Industrial Wastes, 30(6):821-825, June 1958.

6. Personal communications from R. A. Sullivan, Autotrol Corporation, Milwaukee, Wisconsin, to J. A. Heidman and R. C. Brenner, USEPA, Cincinnati, Ohio, April 14, 1982.

7. Kornegay, B. H. and J. F. Andrews. Characteristics and Kinetics of Biological Fixed Film Reactors. FWPCA-17050-00/70, NTIS PB-199 834/BE, 1970.

8. Whalen, W. J., H. R. Bungay, and W. M. Sanders. Microelectrode Determination of Oxygen Profiles in Microbial Slime Systems. Environmental Science and Technology, 3(12):1297-1298, December 1969.

9. Famularo, J., J. W. Mueller, and T. J. Mulligan. Verification Studies of the Biofilm Model for Bacterial Substrate Utilization. Journal WPCF, 50(4):653- 671, April 1978.

10. Zeevalkink, J. A., P. Kelderman, D. C. Visser, and C. Boelhouwer. Physical Mass Transfer in a Rotating Disc Gas-Liquid Contactor. Water Research, 13(9): 913-919, 1979.

11. Grady, C. P. L., Jr. and H. C. Lim. Biological Wastewater Treatment. Marcel Dekker, New York City, 1980.

12. Williamson, K. and P. L. McCarty. A Model of Substrate Utilization by Bacterial Films. Journal WPCF, 48(1):9-24, January 1976.

13. Williamson, K. and P. L. McCarty. Verification Studies of the Biofilm Model for Bacterial Substrate Utilization. Journal WPCF, 48(2):281-296, February 1976.

14. Harremoes, P. Biofilm Kinetics. In: Water Pollution Microbiology, Vol. 2, Ed. by R. Mitchell, Wiley - Interscience, New York City, 1978.

15. Autotrol Wastewater Treatment Systems Design Manual. Autotrol Corporation, Bio-Systems Division, Milwaukee, Wisconsin, 1978.

16. Clow Envirodisc Rotating Biological Contactor Systems Catalog. Clow Corporation, Florence, Kentucky, 1980.

17. Gutierrez, A., I. L. Bogert, O. K. Scheible, and T. J. Mulligan. Upgrading Primary Tanks with Rotating Biological Contactors. EPA-600/2-80-003, NTIS PB80-203771, March 1980.

18. Painter, H. A. Microbial Transformations of Inorganic Nitrogen. Presented at the Conference on Nitrogen as a Water Pollutant, Copenhagen, August 1975; Available in: Progress in Water Technology, 8(4/5):3-29, 1977.

19. Borchardt, J. A., S. J. Kang, and T. H. Chung. Nitrification of Secondary Municipal Waste Effluents by Rotating Bio-Discs. EPA-600/2-78-061, NTIS PB-285 240/8BE, June 1978.

20. Advanced Wastewater Pilot Plant Treatment Studies. Report prepared for City of Indianapolis by Reid, Quebe, Allison, Wilcox, and Associates, Inc., Indianapolis, Indiana, January 1975.

21. Reh, C. W., T. E. Wilson, and R. Srinivasaraghavan. An Approach to Design of RBC's for Treatment of Municipal Wastewater. Presented at the ASCE National Environmental Engineering Conference, Nashville, Tennessee, July 1977.

22. Crawford, P. M. Use of Rotating Biological Contactors for Nitrification at the City of Guelph Water Pollution Control Plant, Guelph, Ontario, Canada. In: Proceedings of the 1st National Symposium/Workshop on Rotating Biological Contactor Technology, Vol. II, EPA-600/9-80-046b, NTIS PB81-124547, June 1980. pp. 1247-1273.

23. Pano, A., E. J. Middlebrooks, and J. H. Reynolds. The Kinetics of Rotating Biological Contactors Treating Domestic Wastewater. Water Quality Series UWRL/Q-81/04, Utah State University, College of Engineering, Logan, Utah, September 1981.

24. Antonie, R. L. Nitrogen Control with the Rotating Biological Contactor. Autotrol Corporation brochure, Milwaukee, Wisconsin, (No date).

25. Workshop on RBC Research Needs (Discussion). In: Proceedings of the 1st National Symposium/Workshop on Rotating Biological Contactor Technology, Vol. II, EPA-600/9-80-046b, NTIS PB81-124547, June 1980. pp. 1429-1461.

26. Hynek, R. J. and C. C. Chou. Development and Performance of Air-Driven Rotating Biological Contactors. In: Proceedings of the 34th Industrial Waste Conference, Purdue University, West Lafayette, Indiana, May 8-10, 1979; Ann Arbor Science, Ann Arbor, Michigan, 1980. pp. 805-815.

27. Hoehn, R. C. and A. D. Ray. Effects of Thickness on Bacterial Film. Journal WPCF, 45(11):2302-2320, November 1973.

28. Sanders, W. M., III. Oxygen Utilization by Slime Organisms in Continuous Culture. Air and Water Pollution, 10(4):253-276, April 1966.

29. Alleman, J. E., J. A. Veil, and J. T. Canady. Scanning Electron Microscope Evaluation of Rotating Biological Contactor Biofilm. Water Research, 16(5):543-550, 1982.

30. CRC Handbook of Microbiology. Vol. I: Bacteria. 2nd Edition, Ed. by A. I. Laskin and H. A. Lechevalier, CRC Press, Cleveland, Ohio, 1977.

31. Torpey, W., H. Heukelekian, A. J. Kaplovsky, and L. Epstein. Effects of Exposing Slimes on Rotating Discs to Atmospheres Enriched with Oxygen. Presented at the 6th International Conference on Water Pollution Research, Jerusalem 18-23, 1972; Available in: Advances in Water Pollution Research, Permagon Press, New York City, 1973. pp. 405-415.

32. Huang, J. C. Operational Experience of Oxygen Enriched Rotating Biological Contactors. In: Proceedings of the 1st National Symposium/Workshop on Rotating Biological Contactor Technology, Vol. I, EPA-600/9-80-046a, NTIS PB81-124539, June 1980. pp. 637-659.

33. Binitanjia, H. H. J., J. J. Brunsmann, and C. Boelhouwer. The Use of Oxygen in a Rotating Disc Process. Water Research, 10(6):561-565, 1976

34. Severin, B. F., H. Brociner, J. E. Dumanowski, J. T. Su, and M. M. Gurvitch. Empirical Oxygen Transfer Relation in the RBC Process. In: Proceedings of the 1st National Symposium/Workshop on Rotating Biological Contactor Technology, Vol. II, EPA-600/9-80-046b, NTIS PB81-124547, June 1980. pp. 1077-1100.

35. Huang, J. C. Workshop on RBC Research Needs (Discussion). Ibid. p. 1445.

36. Chesner, W. H. and J. Iannone. Review of Current RBC Performance and Design Procedures. Report prepared for USEPA, Municipal Environmental Research Laboratory, Cincinnati, Ohio, under Contract No. 68-02-2775 by Roy F. Weston, Inc., (Publication pending).

37. McCann, K. J. and R. A. Sullivan. Aerated RBC's - What are the Benefits. In: Proceedings of the 1st National Symposium/Workshop on Rotating Biological Contactor Technology, Vol. I, EPA-600/9-80-046a, NTIS PB81-124539, June 1980. pp. 515-523.

38. Chou, C. C. Oxygen Transfer Capacity of Clean Media Pilot Reactors at South Shore. Autotrol Corporation memorandum, Milwaukee, Wisconsin, August 23, 1978.

39. Opatken, E. J. Rotating Biological Contactors - Second Order Kinetics. In: Proceedings of the First International Conference on Fixed-Film Biological Processes, Vol. I, EPA-600/9-82-023a, Kings Island, Ohio, April 20-23, 1982. pp. 210-232.

40. Scheible, O. K. and J. J. Novak. Upgrading Primary Tanks with Rotating Biological Contactors. In: Proceedings of the 1st National Symposium/Workshop on Rotating Biological Contactor Technology, Vol. II, EPA-600/9-80-046b, NTIS PB81-124547, June 1980. pp. 961-996.

41. Lyco Wastewater Products - RBS Systems Catalog. Lyco Division of Remsco Associates, Marlboro, New Jersey, 1982.

42. Roy F. Weston, Inc. RBC DIS Subtask on RBC Design Approaches. Internal report prepared for USEPA under Contract No. 68-03-3019, Cincinnati, Ohio, March 5, 1982.

43. Banerji, S. K. ASCE Water Pollution Management Task Committee Report on Rotating Biological Contactor for Secondary Treatment. In: Proceedings of the 1st National Symposium/Workshop on Rotating Biological Contactor Technology, Vol. I, EPA-600/9-80-046a, NTIS PB81-124539, June 1980. pp. 31-52.

44. RBC systems brochure for Manufacturer X, 1978.

45. Process Design Manual for Nitrogen Control. EPA-625/1-75-007, USEPA, Center for Environmental Research, Cincinnati, Ohio, October 1975.

46. Painter, H. A. A Review of Literature on Inorganic Nitrogen Metabolism in Microorganisms. Water Research, 4(6):393-450, 1970.

47. Haug, R. T. and P. L. McCarty. Nitrification with the Submerged Filter. Final report for Grant No. 17010 EPM, USEPA, Municipal Environmental Research Laboratory, Cincinnati, Ohio, August 1971.

48. Notes on Water Pollution No. 52. Water Research Centre, Stevenage, England, 1971.

49. Gujer, W. and D. Jenkins. The Contact Stabilization Process - Oxygen and Nitrogen Mass Balances. SERL Report No. 74-2, University of California, Sanitary Engineering Research Laboratory, Berkeley, California, February 1974.

50. Stratta, J. M. and D. A. Long. Nitrification Enhancement Through pH Control with Rotating Biological Contactors. Final report prepared for USA Medical Research and Development Command under Contract No. DAMD17-79-C-9110 by Pennsylvania State University, September 1981.

51. Ito, K. and T. Matsuo. The Effect of Organic Loading on Nitrification in RBC Wastewater Treatment Processes. In: Proceedings of the 1st National Symposium/Workshop on Rotating Biological Contactor Technology, Vol. II, EPA-600/9-80-046b, NTIS PB81-124547, June 1980. pp. 1165-1175.

52. Knowles, G., A. L. Downing, and M. J. Barrett. Determination of Kinetic Constants for Nitrifying Bacteria in Mixed Culture, with the Aid of an Electronic Computer. Journal of General Microbiology, 38:263-278, 1965.

53. Downing, A. L. and A. P. Hopwood. Some Observations on the Kinetics of Nitrifying Activated Sludge Plants. Schweiz. Zeitsch f Hydrol, 26(2):271-288, 1964.

54. Poduska, R. A. and J. F. Andrews. Dynamics of Nitrification in the Activated Sludge Process. In: Proceedings of the 29th Industrial Waste Conference, Purdue University, West Lafayette, Indiana, May 7-9, 1974. pp. 1005-1025.

55. Balakrishnan, S. and W. W. Eckenfelder, Jr. Nitrogen Relationships in Biological Waste Treatment Processes - I, Nitrification in the Activated Sludge Process. Water Research, 3(1):73-81, 1969.

56. Lawrence, A. W. and C. G. Brown. Design and Control of Nitrifying Activated Sludge Systems. Journal WPCF, 48(7):1779-1803, July 1976.

57. Loehr, R. C., T. B. S. Prakasam, E. G. Srinath, and Y. D. Joo. Development and Demonstration of Nutrient Removal from Animal Wastes. EPA-R2-73-095, NTIS PB-217 887/9BE, January 1973.

58. Wuhrmann, K. Research Developments in Regard to Concept and Base Values of the Activated Sludge System. In: Advances in Water Quality Improvement, Ed. by E. F. Gloyna and W. W. Eckenfelder, Jr., University of Texas Press, Austin, Texas, 1968. pp. 143-170.

59. Sanders, F. M. and R. L. Pope. Nitrification with Rotating Biological Contactor Systems. ERC Report No. 06-78, Georgia Institute of Technology, Environmental Research Center, Atlanta, Georgia, October 1978.

60. Murphy, K. L., P. M. Sutton, R. W. Wilson, and B. E. Jank. Nitrogen Control: Design Considerations for Supported Growth Systems. Journal WPCF, 49(4):549-557, April 1977.

61. Letter (data) communication from R. A. Sullivan, Autotrol Corporation, Milwaukee, Wisconsin, to R. C. Brenner, USEPA, Cincinnati, Ohio, March 12, 1982.

62. Randtke, S. J., G. F. Parkin, J. V. Keller, J. O. Leckie, and P. L. McCarty. Soluble Organic Nitrogen Characteristics and Removal. EPA-600/2-78-030, NTIS PB-281 727/8BE, March 1978.

63. Barth, E. F. and R. L. Bunch. Biodegradation and Treatability of Specific Pollutants. EPA-600/9-79-034, NTIS PB80-106438, October 1979.

64. Mueller, J. A., P. Paquin, and J. Famularo. Nitrification in Rotating Biological Contactors. Journal WPCF, 52(4):688-710, April 1980.

65. Water Pollution Research Board. Water Pollution Research. 1964; Her Majesty's Stationery Office, London, 1965.

66. Letter communication from A. D. Schwer, Metropolitan Sewer District of Greater Cincinnati (Ohio), to D. S. Parker, Brown and Caldwell Consulting Engineers, Walnut Creek, California, March 9, 1971.

67. Wuhrmann, K. Effects of Oxygen Tension on Biochemical Reactions in Sewage Purification. In: Advances in Biological Treatment, Ed. by W. W. Eckenfelder, Jr. and J. McCabe, Permagon Press, New York City, 1963.

68. Stankewich, M. J., Jr. Biological Nitrification with the High Purity Oxygenation Process. In: Proceedings of the 27th Industrial Waste Conference, Purdue University, West Lafayette, Indiana, May 2-4, 1972. pp. 1-23.

69. Nagel, C. A. and J. G. Haworth. Operatonal Factors Affecting Nitrification in the Activated Sludge Process. Presented at the 42nd Annual Conference of the WPCF, Dallas, Texas, October 1969; Available as a reprint from the County Sanitation Districts of Los Angeles County.

70. Hitdlebaugh, J. A. and R. D. Miller. Operational Problems with Rotating Biological Contactors. Journal WPCF, 53(8):1283-1293, August 1981.

71. Letter (data) communication from W. L. Morley, Wastewater Treatment Plant, Gladstone, Michigan, to R. C. Brenner, USEPA, Cincinnati, Ohio, November 17, 1981.

72. Downing, A. L. and G. Knowles. Population Dynamics in Biological Treatment Plants. Presented at the 3rd International Conference on Water Pollution Research, Munich, September 1966; Available in: Advances in Water Pollution Research, Vol. 2, Water Pollution Control Federation, Washington, D.C., 1967. pp. 117-142.

73. Albert, J. L. Use of Supplemental Aeration and pH Adjustment to Improve Nitrification in a Full-Scale Rotating Biological Contactor System. In: Proceedings of the First International Conference on Fixed-Film Biological Processes, Vol. II, EPA-600/9-82-023b, Kings Island, Ohio, April 20-23, 1982. pp. 633-657.

74. Mulbarger, M. C. The Three Sludge System for Nitrogen and Phosphorus Removal. Presented at the 44th Annual Conference of the WPCF, San Francisco, California, October 1971.

75. Interaction of Heavy Metals and Biological Sewage Treatment Processes. USPHS, Division of Water Supply and Pollution Control, May 1965.

76. Letter report from Brown and Caldwell Consulting Engineers, Walnut Creek, California, to Valley Community Services District, Dublin, California, March 1974.

77. Anthonisen, A. C., R. C. Loehr, T. B. S. Prakasam, and E. G. Srinath. Inhibition of Nitrification by Ammonia and Nitrous Acid. Journal WPCF, 48(5):835-852, May 1976.

78. Letter communication from C. N. Sawyer, self employed, Sun City, Arizona, to D. S. Parker, Brown and Caldwell Consulting Engineers, Walnut Creek, California, January 24, 1975.

79. Personal communication from G. W. Davis, B. F. Goodrich Company, Brecksville, Ohio, to D. S. Parker, Brown and Caldwell Consulting Engineers, Walnut Creek, California, August 1974.

80. United States Patent 3,869,380. March 4, 1975.

81. Dallaire, G. U.S.'s Largest Rotating Biological Contactor Plant to Slash Energy Use 30%. Civil Engineering, ASCE, 49(1):70-72, January 1979.

82. Harremoes, P. and M. Riemer. Pilot-Scale Experiments on Down-Flow Filter Denitrification. Presented at the Conference on Nitrogen as a Water Pollutant, Cophehagen, August 1975; Available in: Progress in Water Technology, 8(4/5):557-576, 1977.

83. Jeris, J. S., C. Beer, and J. A. Mueller. High Rate Biological Denitrification Using a Fluidized Bed. Journal WPCF, 46(9):2118-2128, September 1974.

84. Christensen, M. H. and P. Harremoes. Biological Denitrification of Sewage: A Literature Review. Presented at the Conference on Nitrogen as a Water Pollutant, Copenhagen, August 1975; Available in: Progress in Water Technology, 8(4/5):509-555, 1977.

85. Blanc, F. C., J. C. O'Shaughnessy, D. J. Connick, and D. Wood. Denitrification of Nitrified Municipal Wastewater Using Rotating Biological Contactors. In: Proceedings of the 1st National Symposium/Workshop on Rotating Biological Contactor Technology, Vol. II, EPA-600/9-80-046b, NTIS PB81-124547, June 1980. pp. 1275-1300.

86. Rittman, B. E. and P. L. McCarty. Design of Fixed-Film Processes with Steady-State-Biofilm Model. Presented at the 10th International Conference on Water Pollution, Toronto, June 23-27, 1980; Available in: Progress in Water Technology, 12(6):271-281, 1980.

87. Camp, T. R. Sedimentation and Design of Settling Tanks. Proceedings of the ASCE, 71:445-486, 1945.

88. Srinivasaraghavan, R., C. W. Reh, and S. Liljegren. Performance Evaluation of Air Driven RBC Process for Municipal Waste Treatment. In: Proceedings of the 1st National Symposium/Workshop on Rotating Biological Contactor Technology, Vol. I, EPA-600/9-80-046a, NTIS PB81-124539, June 1980. pp. 525-552.

89. Smith, D. A., C. P. Poon, and R. D. Miller. Upgrading DA Trickling-Filter Sewage Treatment Plants. Technical Report No. N-102, USA Corps of Engineers, Construction Engineering Research Laboratory, Champaign, Illinois, May 1981.

90. Personal communication from D. A. DeCarlo, Burgess and Niple, Ltd., Columbus, Ohio, to J. A. Heidman, USEPA, Cincinnati, Ohio, April 14, 1982.

91. Kincannon, D. F. and J. H. Sherrard. Trickling Filter Versus Activated Sludge - When to Select Each Process. Proceedings of the 28th Industrial Waste Conference, Purdue University, West Lafayette, Indiana, May 1-3, 1973. pp. 69-75.

SECTION 3

EQUIPMENT

3.1 Introduction

Six manufacturers were marketing RBC units in the United States at the time of document preparation and provided input for this section (1)(2)(3)(4)(5)(6). As stated in the Foreword, one manufacturer (Manufacturer X) has since stopped marketing RBC's and descriptions and evaluations of its equipment components have been removed herefrom. This section, therefore, covers only the equipment of the five current manufacturers: Autotrol (now Envirex), Clow, Crane-Cochrane, Lyco, and Walker Process.

Each manufacturer designs the RBC with an individuality that is unique to its firm. Consequently, RBC's differ from one another in practically every component used in their assembly, including shafts, plastic media configurations, methods for separating the individual discs, methods of supporting the plastic media, bearings, and drives. Competition between the manufacturers encourages technical innovations that they expect to translate into marketing advantages. Because of this competition, most of the manufacturers have progressed through several generations of design, production, and testing of the individual components that make up their finished products.

In spite of continuing industry-wide efforts to produce a highly cost effective and reliable process, mechanical failures of RBC equipment have been experienced at a number of locations (7). Failures have occurred with shafts, media, bearings, and drives. Many of the causes of these failures have been corrected by proprietary redesign of the failed component. It is important to realize that RBC's were placed in service in the United States following a somewhat abbreviated pilot development program that was not well suited to assessing the long-term reliability of equipment. Mechanical treatment plants must operate 24 hr/day, 365 days/yr, and equipment that appears to be satisfactory during intermittent pilot plant studies may fail when it is required to operate and perform under "real world" conditions.

This section illustrates and discusses the wide variation in alternatives available in the makeup of an RBC unit. The developmental status of key system components is also addressed. It is the responsibility of the designer to evaluate the equipment options and determine which components and assembly are best suited for his specific application.

3.2 General Equipment Description

RBC's are cylindrical-type structures consisting of plastic media attached to and/or supported by rotating shafts. The media of four of the manufacturers are formed as discs and aligned perpendicular to the shaft. The media of the fifth manufacturer, Walker Process, are spirally wound onto and aligned parallel with the shaft. Biomass adheres to and grows on the media, thus categorizing the RBC process as a fixed film biological process. The fundamental dimensions of an RBC assembly are shaft length and media diameter. The shaft length and the disc spacing employed by a particular manufacturer determines the number of discs on each shaft. Maximum shaft length is structurally limited presently to approximately 27 ft, with 25 ft occupied by media. Maximum media diameter is limited to 12 ft, set by the maximum allowable road vehicle height of 14 ft. These maximum dimensions are representative of the typical modular RBC unit. The discs are spaced on the shaft according to various plastic configurations and have a thickness of approximately 50 mils (0.05 in.). The number of discs per shaft and the diameter of the discs determine the media surface area available for attached biological growth and biochemical reactions. Media surface area is the principal determinant of the number of RBC units or modules required for a particular wastewater treatment facility.

The RBC manufacturers offer a variety of shaft lengths less than 27 ft and media diameters less than 12 ft. These smaller units are utilized where the surface area requirement is less than that provided by the typical modular unit and for pilot-scale evaluations.

3.3 Equipment Components

3.3.1 Shafts

RBC shafts are used to support and rotate the plastic media and expose the plastic surfaces to alternating cycles of wastewater and atmospheric air. The shafts are fabricated from steel and are covered with a heavy protective coating suitable for water and high humidity service.

Proper protective coating procedure requires sand blasting of the steel shaft prior to application to ensure acceptable metal preparation. A coal tar epoxy is normally used as the protective coating with a minimum film thickness of 14 mils (0.014 in.). The performance of coal tar epoxy coatings has, in general, been satisfactory to date. Current data, however, are inadequate to predict whether these coatings will protect shafts from corrosive effects throughout a 20-yr design life.

Michanically-driven shafts are generally rotated at a speed of 1.6 rpm, which equates to a peripheral or tip speed of 60 fpm. The maximum practical speed of rotation is 2.2 rpm, equivalent to a maximum peripheral speed of 83 ft/min.

Air-drive RBC units operate at rotational speeds of 1.0 to 1.4 rpm, or tip speeds of 38 to 53 ft/min. The higher rotational speeds are normally employed at the front end of an RBC train in the first and second stages. The lower speeds of rotation are used in the latter stages of an RBC train where oxygen demand is lower.

Each manufacturer designs its own shape, size, and thickness of shaft. The thickness is governed by structural requirements, and the shape is highly dependent on the method the manufacturer employs in supporting the plastic media from the shaft. The five manufacturers each utilize a shaft that differs from the others in either thickness, size, or shape, or in some cases all three. Structurally, these differences are readily apparent as identified in Table 3-1 and shown in Figure 3-1. Lyco currently manufactures Series 300 circular shafts. The previous Lyco/Hormel Series 200 octagonal shaft is also included in Table 3-1 and Figure 3-1 because of the large number of installations still using it.

3.3.2 Media

3.3.2.1 General Description

The heart of the RBC process is the plastic media. The removal of organics and/or oxidation of ammonia nitrogen are achieved by the rotation of the

TABLE 3-1. SHAFT CHARACTERISTICS

Manufacturer	Shape	Size (in.)	Thickness (in.)	Section Modulus ($in.^3$)	Ref.
Autotrol	Square	16 x 16	1.00	282	1
Clow	Round	30	0.625	415	2
Crane-Cochrane	Round	30	0.75	492	8
Lyco	Round	28	0.75	426	4
Lyco/Hormel	Octagonal	24	0.75	344	4
Walker Process	Round	30	0.75	492	6

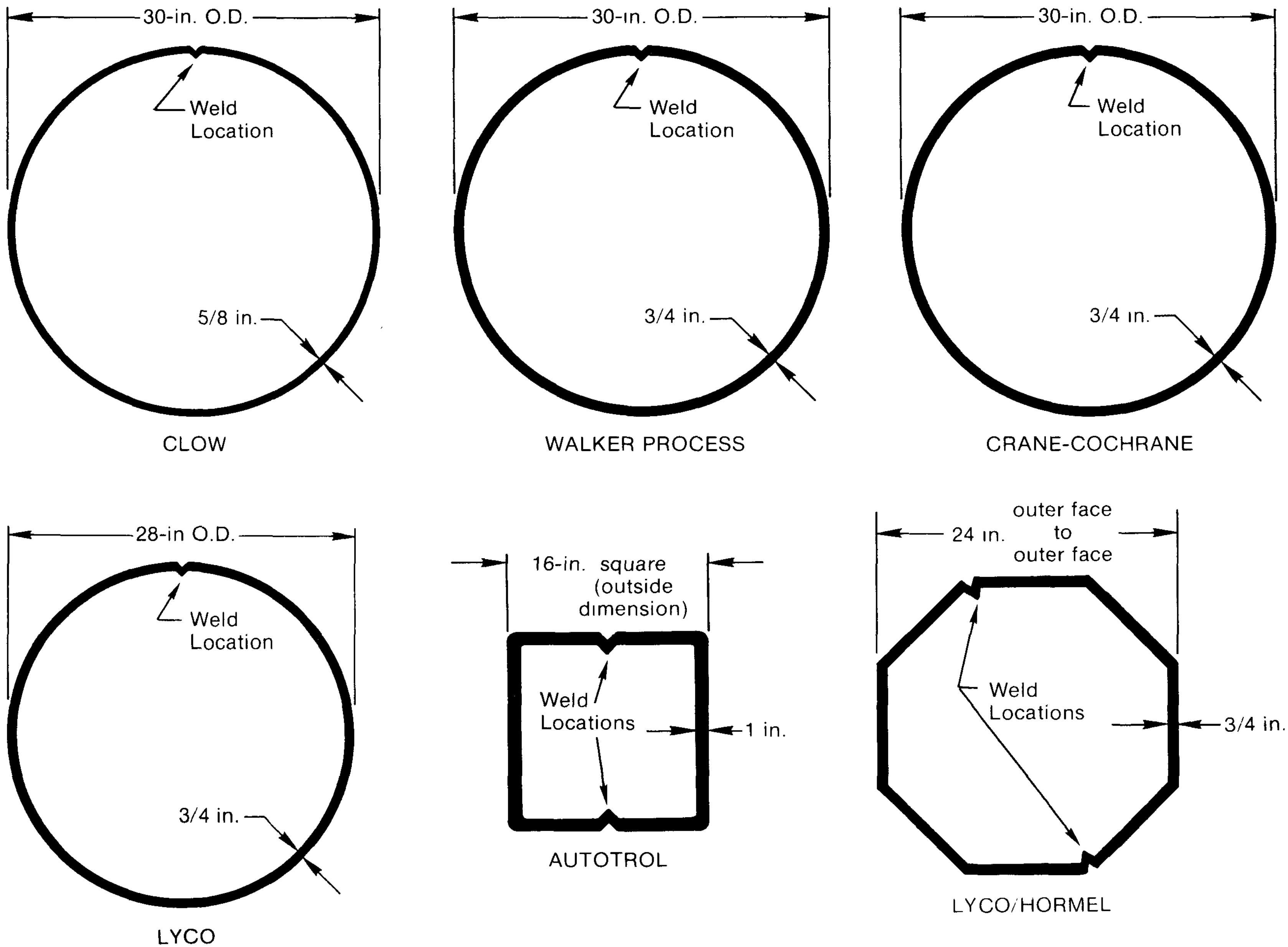


Figure 3-1. Cross-sections of RBC shafts.

media through the wastewater, which enables the attached biofilm to contact the substrate, and then through the air to achieve oxygen transfer into the film of wastewater and then into the biofilm itself.

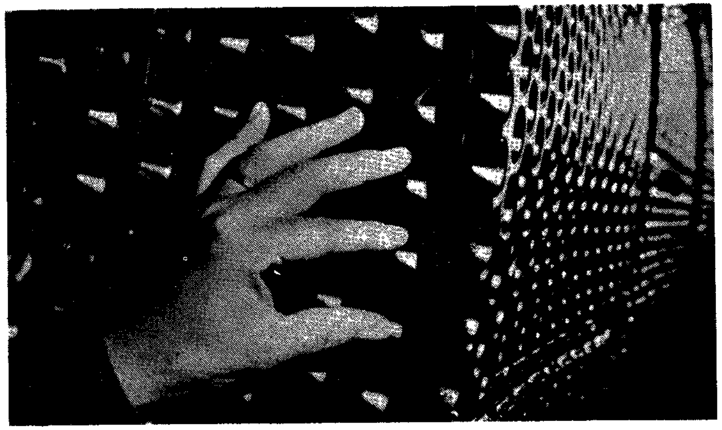
When RBC's were first installed in the United States, the technology employed was a carry-over from Europe where plastic discs were fabricated from expanded polystyrene. Each disc was approximately 0.5 in. thick, and the spacing between discs was 1.33 in. This type of disc arrangement had an available surface area of approximately 23,000 sq ft for an 18-ft long shaft and a disc diameter of 12 ft. In 1972, the polyethylene disc was introduced as a cost reduction alternative to polystyrene. The major advantage of polyethylene is its ability to be formed into various corrugations that require a thickness of only 40 to 60 mils (0.04 to 0.06 in.). This innovation enabled 100,000 to 180,000 sq ft of surface area to be provided on the same 27-ft shaft with 12-ft diameter media. Today, all U.S. manufacturers of RBC's utilize polyethylene as their plastic media.

Polyethylene is a complex organic compound of the polyolefin polymer family. This family includes a complete range of low, medium, high, and extra high density polymers whose specific weight ranges from 57 to 60 lb/cu ft (7). The feed stock, catalysts, method of manufacture, and other olefins added to the polyethylene determine the type and degree of branching, which in turn determine the physical characteristics of the final polymer. Although ethylene can be polymerized to form various types of polyethylene, the norm in current practice is to add butene or hexene to the ethylene to produce polyethylene co-polymers, which enhance the material's physical properties (9). The high density polyethylenes (HDPE's) used in present-day RBC units are all co-polymers.

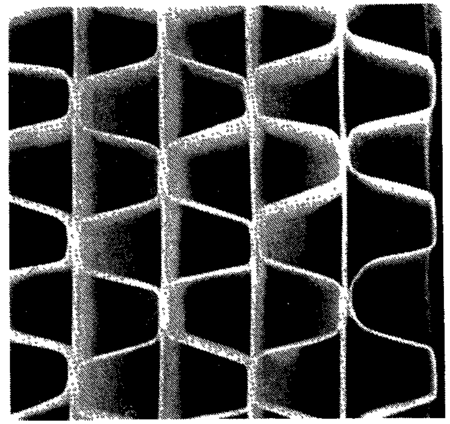
3.3.2.2 Configurations

Various media configurations or corrugation patterns have been selected by the manufacturers, each with its own claimed advantages. There are several reasons for using configurations. Configurations add stiffness to the HDPE sheets and enable these sheets to be formed with diameters as large as 12 ft. Configurations increase the available surface area by 15 to 20 percent. Configurations cause the wastewater to follow a tortuous path through the media, thus increasing wastewater exposure time to the air for greater oxygen transfer in the atmospheric sector of the rotational cycle. Configurations also stimulate air turbulence in the atmospheric sector of the cycle, again leading to improved oxygen transfer. Finally, configurations are used as spacers to keep the sheets separated.

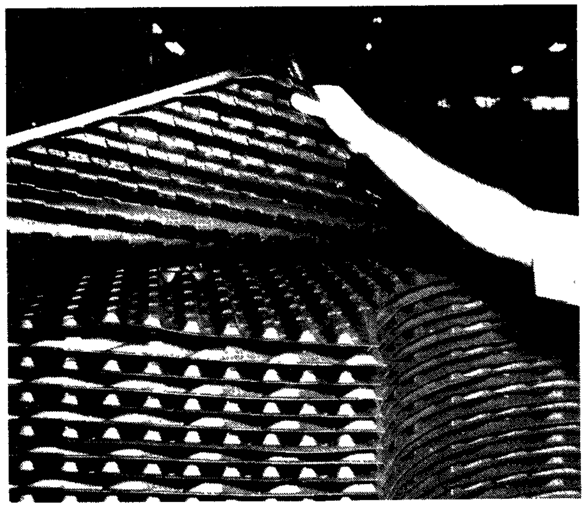
Each of the above reasons are qualitative; no comparative evaluation has been conducted to determine quantitatively the incremental advantage of one configuration over another, or if the advantage can be quantitatively assessed. The different types of media configurations employed by the manufacturers are illustrated in Figure 3-2. All of the manufacturers use



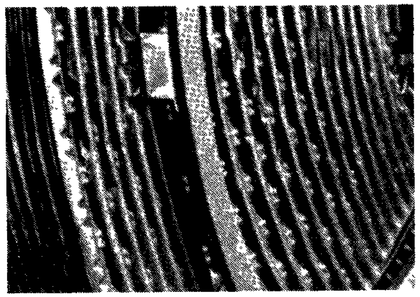
FROM WALKER PROCESS BROCHURE (6)



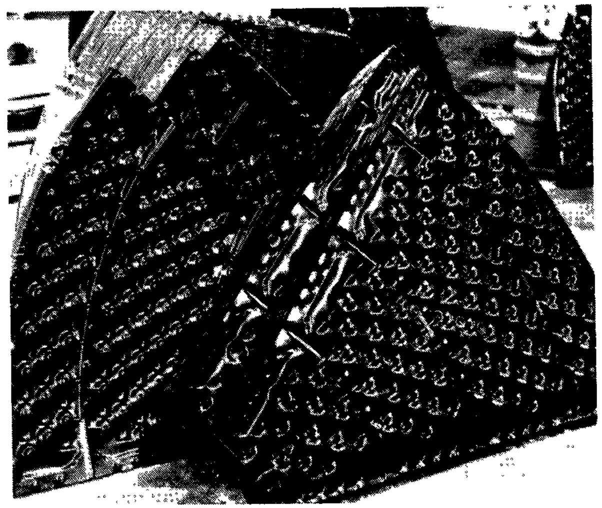
FROM AUTOTROL
DESIGN MANUAL (1)



COURTESY OF CRANE-COCHRANE



COURTESY OF LYCO



COURTESY OF CLOW

Figure 3-2. RBC media configurations.

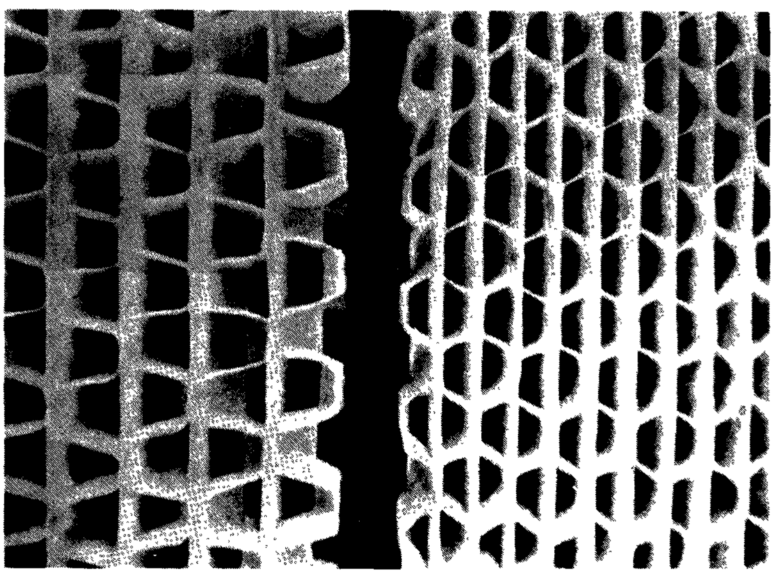
corrugated or honeycomb configurations to achieve increased media surface area and structural stability.

3.3.2.3 Density

Standard density media are normally used in the front stages of an RBC train. Standard density media are defined as media with a surface area of 100,000 sq ft supported on or from a 27-ft long shaft in which the media diameter is approximately 12 ft. By reducing the space required for the repeating plastic configuration by 33 percent, the available surface area can be effectively increased by 50 percent. Media with a surface area of 150,000 sq ft assembled and supported on or from a 27-ft shaft with a media diameter of approximately 12 ft is defined as high density media. Some manufacturers are now also offering media with densities of 120,000 and 180,000 sq ft per 27-ft long shaft for increased design flexibility.

The increase in surface area achieved by reducing the spacing between plastic sheets is displayed in Figure 3-3. High density media have been used primarily in the middle and final stages of an RBC train. Experience with high density media at these specific stage locations has been good, both in terms of biological performance and structural reliability. The increased surface area has not resulted in increased shaft loadings because biofilm growth is considerably less in the middle and latter stages than that normally encountered in the early or front stages. Use of high density media in the lead stages of an RBC train should be avoided except for second-step nitrifica-

STANDARD DENSITY



HIGH DENSITY

Figure 3-3. Autotrol high and standard density media [from Autotrol design manual (1)].

tion applications or where the organic carbon load is known to be very low. A recommended "rule-of-thumb" is to limit slime thickness on high density media to 50 mils (0.05 in.) to provide an acceptable margin of safety against shaft overload and possible fatigue. All of the manufacturers offer high density media so that the designer is not limited to the selection of a single supplier.

3.3.2.4 Assembly and Support

RBC manufacturers employ various methods for supporting plastic media from their shafts. Three of the five manufacturers, Clow, Crane-Cochrane, and Lyco, rely on a coated steel or stainless steel radial arm system to support the plastic media. Clow welds rings to the shaft and then bolts a box-like structure together to contain its plastic media. This technique allows for field assembly of the plastic media and facilitates easy replacement of a media section or wedge. Clow's media pack consists of four sections with eight pie-shaped wedges per section. A schematic of the Clow support assembly is shown in Figure 3-4.

Crane-Cochrane's media are supported by steel arms radiating from rings that are bolted to clips welded to the shaft and are connected to these arms by 2-in. steel pipes penetrating the discs through pre-formed collars. A modular unit contains 36-pie shaped wedges divided into six wedges per section and six sections per shaft as shown pictorially in Figure 3-5.

The Lyco (Series 300) design uses modular, coated steel support ring assemblies with radial members that bolt onto the central round shaft. Center shaft rings are welded to the shaft at and near both ends of the shaft where stresses are low and are attached by means of a grout adhesive in the middle portion of the shaft where stress levels are higher. The support rings are located every 3.5 to 4 ft to divide the media pack into six or seven sections. Each section is comprised of eight pie-shaped wedges supported by 24 rods (three per wedge) that are positioned through integrally molded flanges located in the media. Each section is clamped to the support rings by elastomer grommets. The Lyco support assembly is depicted diagrammatically in Figure 3-6.

The Lyco/Hormel (Series 200) design employed modular assemblies of coated steel rings and radial arms for supporting its plastic media. The rings were fabricated to fit onto Lyco/Hormel's octagonal-shaped shaft and were located every 3.5 to 4 ft to divide the media pack into six or seven sections. Each section was comprised of eight pie-shaped wedges supported by 24 rods (three per wedge) positioned through the plastic media and carried by the radial steel arms. The Lyco/Hormel support assembly is depicted diagrammatically in Figure 3-7.

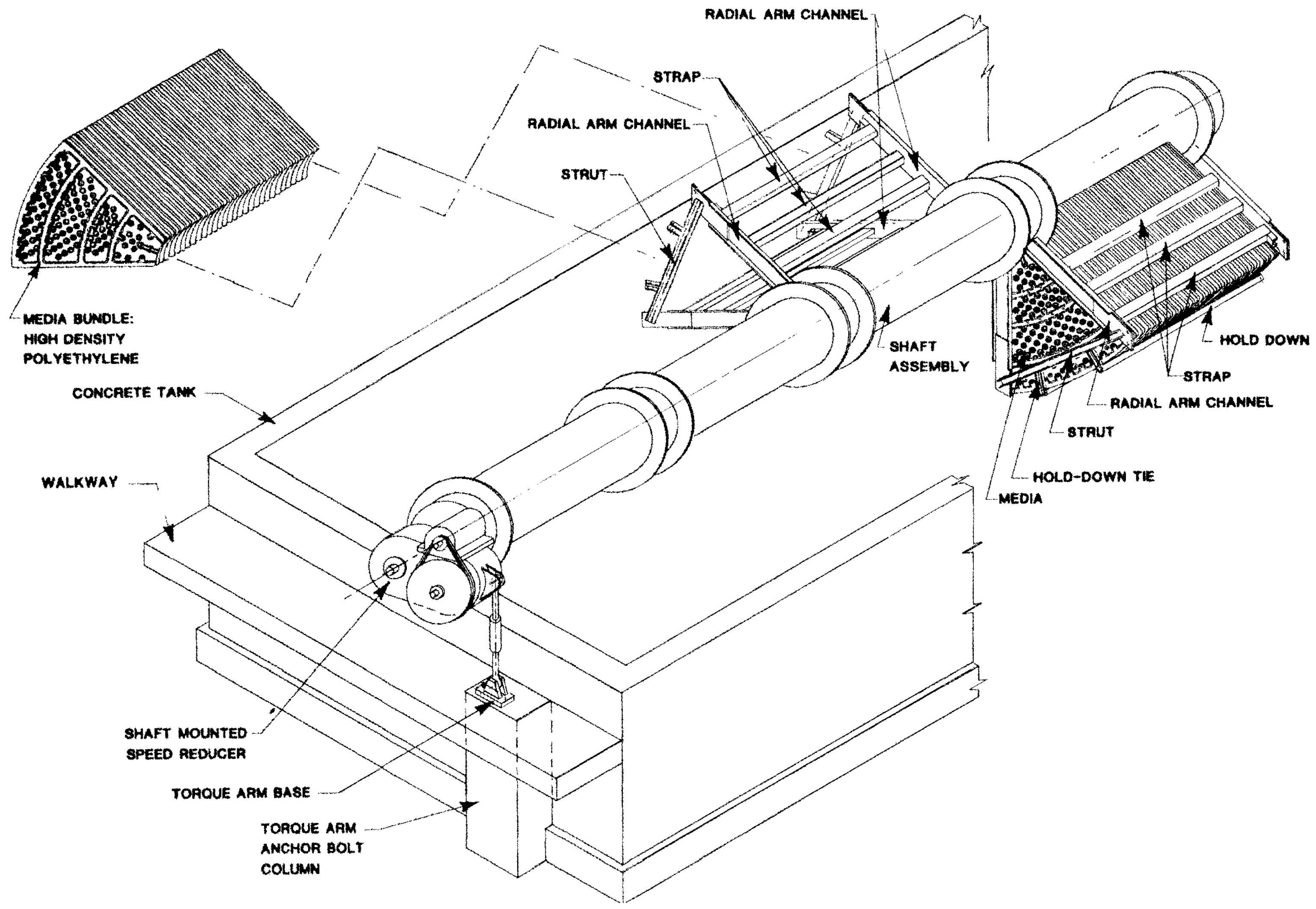


Figure 3-4. Clow media assembly [from Clow catalog (2)].

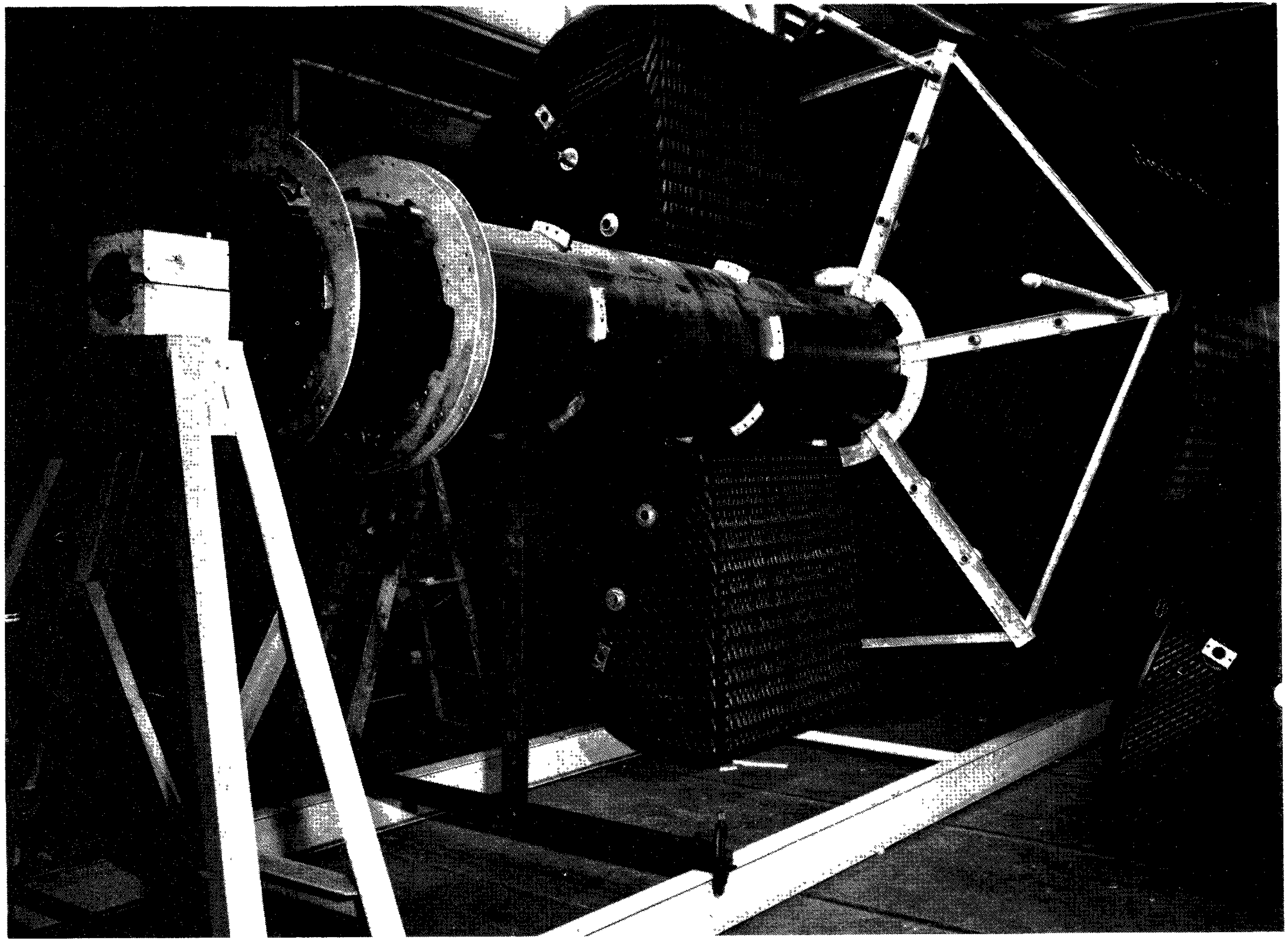


Figure 3-5. Crane-Cochrane media assembly [courtesy of Crane-Cochrane].

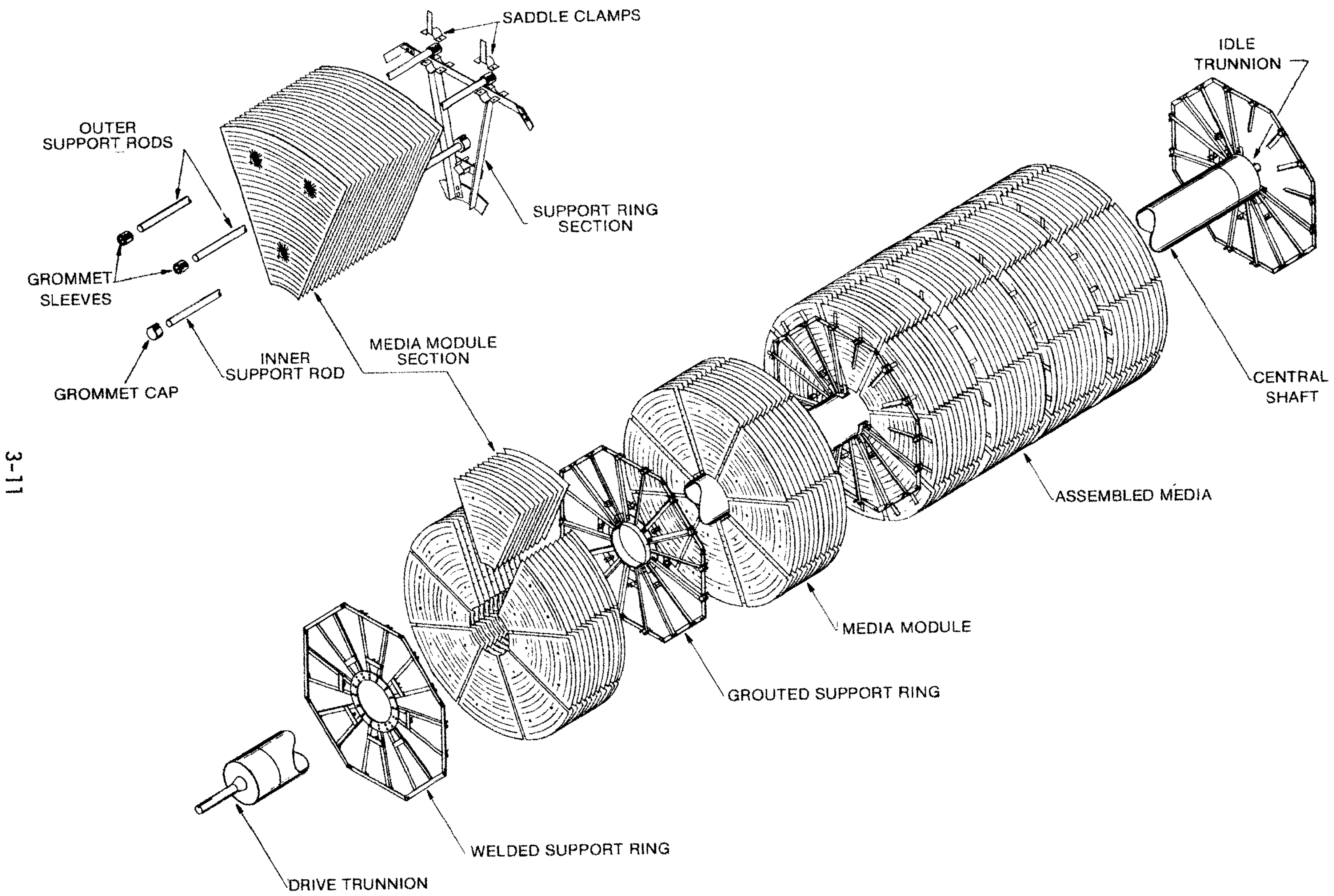


Figure 3-6. Lyco (Series 300) media assembly [from Lyco catalog (4)].

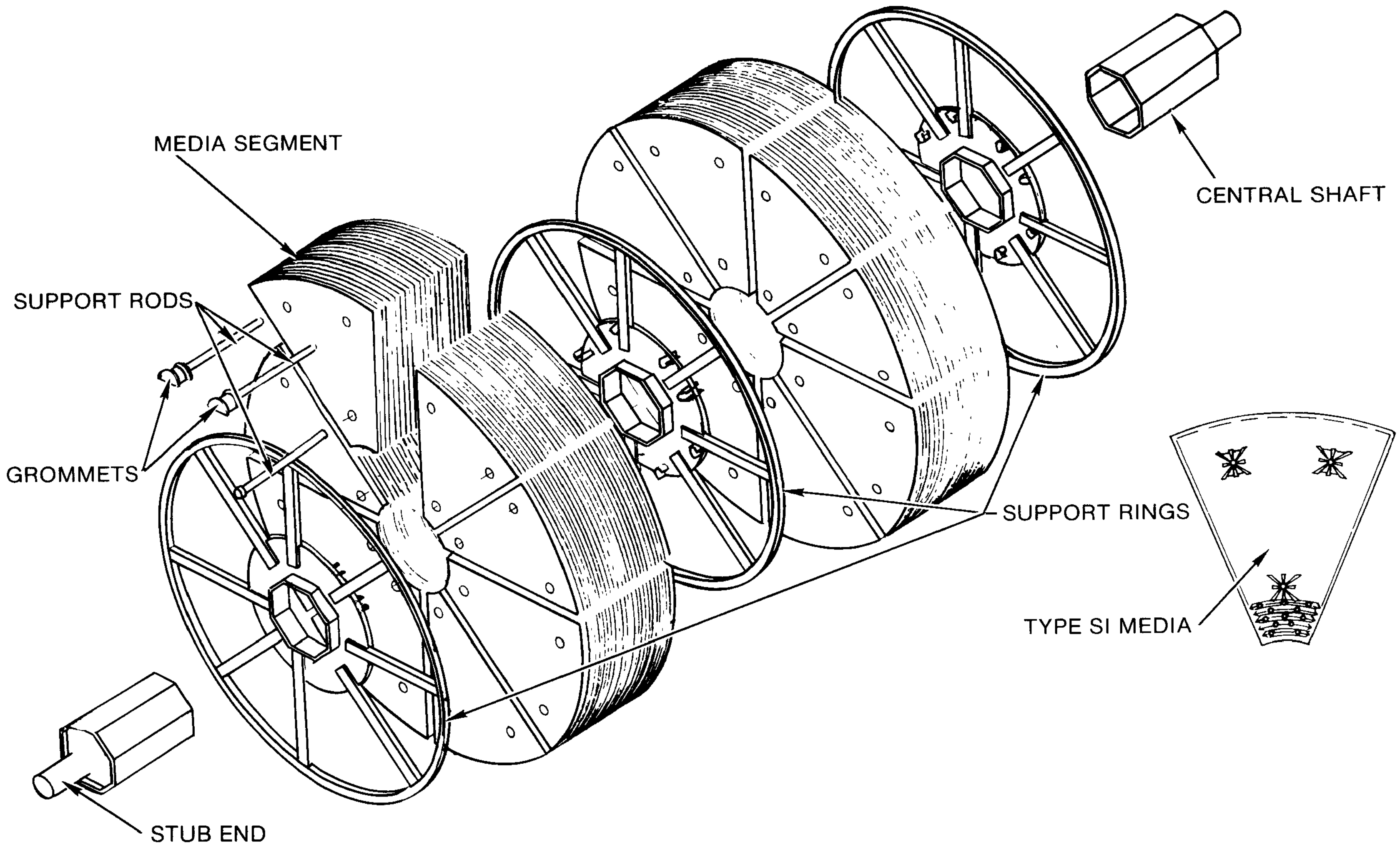


Figure 3-7. Lyco/Hormel (Series 200) media assembly [from Lyco catalog (4)].

In contrast to the radial arm approach, Autotrol employs plastic media hubs that fit onto its square shaft. The plastic media sheets are thermally welded to individual plastic hubs and spotwelded to each other to form a unitized section of 2.5-ft length. As the sections are positioned on the shaft, the plastic hubs are shimmed in place to prevent movement. Ten sections are used per shaft to produce a 25-ft media assembly.

Walker Process also does not utilize a radial arm support system. Rather, plastic media are attached to its shaft with a heavy layer of an epoxy bonding agent and stainless steel strips. The media are spirally wound onto the shaft in 35-in. wide strips. Each spirally-wound media layer is heat welded to the preceding layer forming a monolithic structure (see Figure 3-2). Eight such strips are attached to each shaft to form either the 100,000-sq ft standard density media contactor or the 150,000-sq ft high density media contactor.

A report by Chesner and Iannone (7) discusses the advantages and early problems of systems that employ radial support arms and pie-shaped media wedges. These systems enable the media to be replaced in the field without removing the shaft. They can also prove to be beneficial in transportation since the RBC unit can be broken down into smaller components. Earlier designs of this type had some problems with movement of the media and subsequent damage as the wedges responded to the alternating forces of gravity and buoyancy. More recent designs have reduced movement by tightening the media strap supports or by designing for increased stresses at the interface of the media and support rods.

In designing an RBC system, the engineer must be cognizant of potential operation and maintenance ramifications associated with media replacement. As described above, radial support arm assemblies combined with sections of pie-shaped media wedges (Clow, Crane-Cochrane, and Lyco) are conducive to field replacement of media without removal of the shaft from the RBC tank. The shafts of the other two manufacturers (Autotrol and Walker Process) must be raised and/or removed to accommodate replacement of the media. In the case of Autotrol, damaged media sections must be slid off the end of the shaft. For Walker Process, replacement of the media, which is epoxy bonded to the shaft, can only be accomplished by the manufacturer's personnel, either at the site or after return to the factory.

3.3.3 Drives

3.3.3.1 Mechanical Drive Option

Historically, RBC's have been driven mechanically. Without exception, the mechanical drive packages offered by the manufacturers have provided constant speed capability only. Restricted drive flexibility has traditionally been part of RBC system design philosophy to prevent operator manipulation of rotational speed and possible process upset. The potential advantages of variable speed operation, however, suggest that a change in approach to allow the operator greater latitude in speed selection could improve overall plant performance by achieving greater control of biofilm thickness and DO concentration.

As reported by Chesner and Iannone (7), RBC manufacturers specify factory-assembled drive packages for all mechanical drive equipment, consisting of motors, speed reducers, and drive systems. Reduction of motor output speed down to approximately 1.6 rpm can be accomplished through the use of various combinations of multi-V-belts, gear boxes, and chain-and-sprocket units. Multi-V-belt and chain-and-sprocket units are susceptible to alignment problems, but those in operation have been relatively trouble free. Gear boxes are gaining in popularity because of their efficient energy transfer, low maintenance requirements, and ease of installation and replacement.

The electric motors used for mechanical drive RBC's are normally 3-phase, 60-hertz units. The motors, designed with protective coatings for high humidity environments, are capable of providing long-term reliable service. Mechanical drive power requirements are covered in substantial detail in Section 4. A photograph of a typical mechanical drive package is presented in Figure 3.8.

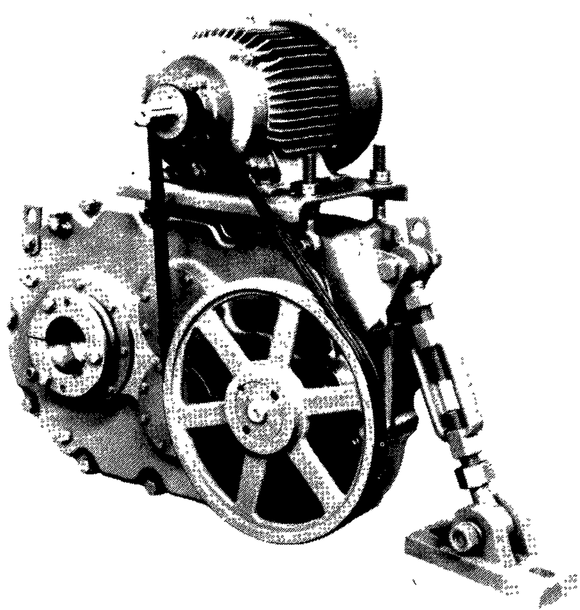


Figure 3-8. RBC mechanical drive assembly (courtesy of Crane-Cochrane).

3.3.3.2 Air Drive Option

A recent development offered by Autotrol is the air drive RBC unit. The air drive assembly consists of plastic cups welded around the outer perimeter of the media. The cups are 4 or 6 in. deep, depending on stage location, to accommodate and collect the air flow. An air header is placed below the media (Figure 3-9), and air is released at a pressure of 3 to 4 psig into the attached cups, creating a buoyant force that causes the shaft to turn. Approximately 20 to 30 percent of the air is not captured by the cups and escapes into the radial passages where it flows upward through the corrugated media. This air movement tends to aid in shearing excess biomass from the plastic media, thereby reducing film thickness and corresponding loads on the shafts.

The operator can vary the rotational speed of air drive shafts by adjusting the air flow to each stage. The recommended procedure is to reduce speed in moving from the first to the final stage. Air flow requirements to maintain various speeds of rotation are covered in greater detail in Section 4.

3.3.4 Bearings

As indicated by Chesner and Iannone (7), bearings are one of the components of an RBC unit requiring periodic maintenance. Some early RBC designs experienced deflections of longer shafts causing unequal wearing of the shaft ends and bearings. The use of self-aligning bearing units appears to have eliminated this condition. Protection from the corrosive effects of wastewater by the use of high moisture bearings and cover plates (idle-end) has minimized another potential problem.

To permit easy access for lubrication and maintenance, the bearings can be located outside the media protective covers. Oversized grease cups can be mounted atop the bearing housings to reduce lubrication manpower. A typical bearing assembly used for RBC's is shown pictorially in Figure 3-10.

3.3.5 Instrumentation

3.3.5.1 Load Cells

Hydraulic load cells are available and in use for periodically measuring total shaft load, which in turn can be used to estimate biofilm thickness. The shaft weighing device consists of a load cell bearing installed on the idle end of a shaft. A hand-operated hydraulic pump is attached to the load cell and used to lift the bearing off its base while the shaft continues to rotate or is momentarily stopped depending on manufacturer.

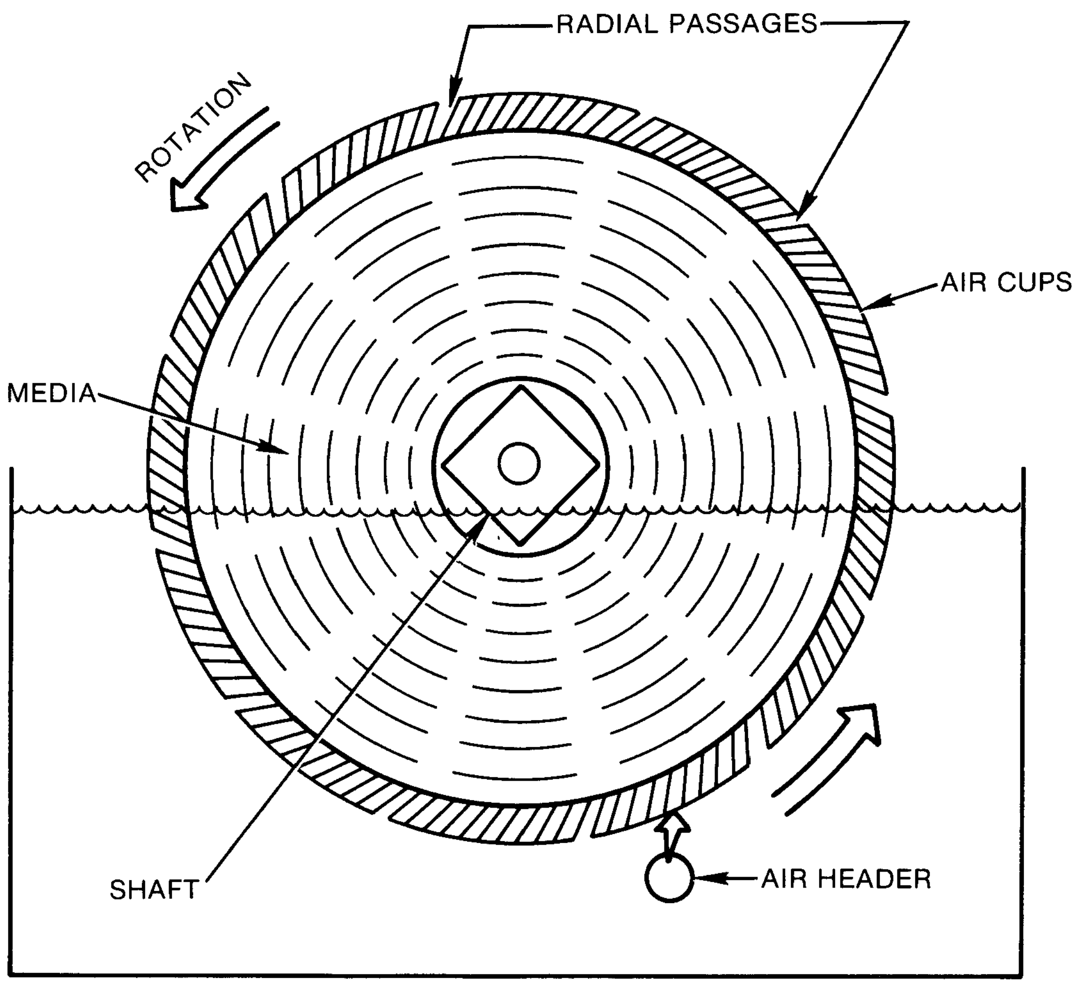


Figure 3-9. Air drive RBC schematic [from Autotrol design manual (1)].

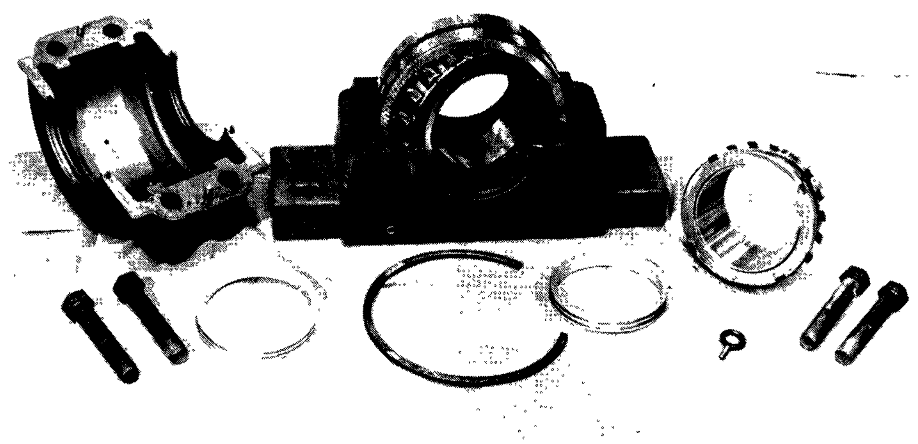


Figure 3-10. RBC shaft bearing assembly (courtesy of Crane-Cochrane).

The resulting hydraulic pressure is read from a gauge. This reading can then be converted to shaft weight (automatically corrected for buoyancy effects) and/or biofilm thickness.

The electronic strain gauge load cell is a recent development that enables shaft load to be measured continuously without lifting the idle-end bearing off its base. A companion weight converter unit is available that when plugged into this type of load cell provides a direct readout in pounds, which again is readily convertible to biofilm thickness. An alarm can be incorporated in the assembly to signal when shaft load reaches a preset percentage of design load. Electronic strain gauge load cells are primarily applicable to new installations as it is difficult and costly to modify existing RBC shaft end walls to accept them.

Since a higher percentage of carbonaceous material is removed in the initial stages, the first and second stages can be expected to experience the thickest biofilm growth and heaviest shaft loads in an RBC train. Load cells strategically located at these and other critical stages can provide the operator with advance notice of a gradual buildup in biofilm thickness. Corrective action can then be initiated if shaft design loads are likely to be exceeded. Possible corrective actions include 1) increasing rotational speed during periods of low loadings (usually in the early morning hours) to increase the film shearing force, 2) adding supplemental air for the same purpose, and 3) increasing media surface area in the affected stage (usually the first stage) by removing the baffle separating it from the succeeding stage to equalize load distribution. An upper limit on biofilm thickness of 75 mils (0.075 in.) is recommended for standard density media to provide adequate protection against shaft overload. The installation and regular use of load cells should be considered an essential feature of sound RBC process operating strategy.

3.3.5.2 Flow Control

RBC trains are normally arranged in parallel modules. Historically, the operator has had to rely on visual observation of semi-continuous weir overflows to maintain equal hydraulic loading to each train. Some operators have expressed concern that lack of positive flow measurement and control leads to unequal flow distribution and randomly overloaded and underloaded trains. Flow measuring weirs or other flow measuring devices coupled with mechanisms for adjusting flow would provide operators with information on and the capability to maintain proper flow distribution. In addition to contributing to improved process performance, balanced flow distribution would automatically tell operating personnel to look elsewhere for the cause of any process upsets encountered.

3.3.5.3 Dissolved Oxygen Monitoring and Control

Strategic DO monitoring is another operational tool that can be used advantageously in RBC process control. The critical locations for monitoring DO are the first and second stages. Falling stage liquor DO levels, particularly in these lead stages, may forewarn of changing conditions conducive to the growth of undesirable Beggiatoa slime (Figure 3-11). Low DO's (less than 2 mg/l) may also indicate a gross increase in either hydraulic or organic loading or both.

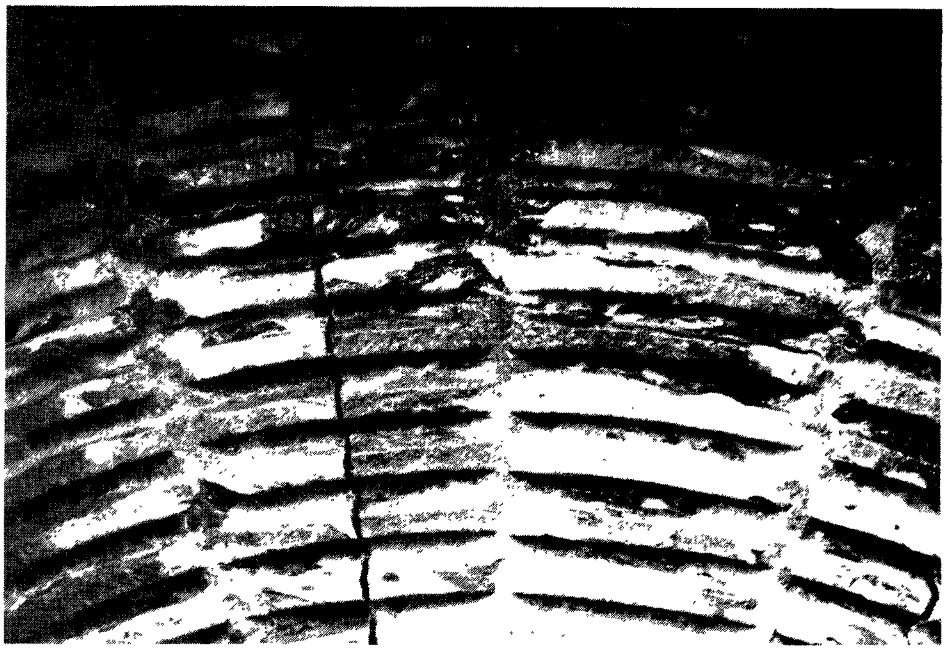
DO instrumentation employed for process control should be serviced frequently to obtain consistently reliable data. Erroneous readings resulting from out-of-calibration meters, ruptured membranes, etc., will soon lead to operator disenchantment with and discarding of the equipment. DO probes should be placed in tank locations that are readily accessible, yet representative of bulk liquid DO concentration. A recommended location is adjacent to the outlet baffle, one-third of the tank width from the idle-end sidewall, and one-third of the liquid depth off the floor.

Equally important to furnishing instrumentation that measures DO is providing the operator with standby cabability to increase DO concentration when necessary. Equipment options that can provide this capability include variable speed drives to allow the speed of rotation to be increased during periods of low DO and supplemental air systems that enable compressed air to be delivered directly to the affected stages. Other alternatives are temporary hydrogen peroxide addition, stage size rearrangement through removal of baffles, and step feeding of incoming flow to several stages. The latter two alternatives, while not adding additional oxygen directly to the wastewater, can decrease oxygen demand rate in an overloaded stage.

a. Variable Speed Drives

If the designer desires, the manufacturers can modify their standard drive packages to include variable speed capability. The additional flexibility thereby afforded would provide the operator with a mechanism to strip excess biofilm growth from the disc media or increase stage liquor DO. Generally, the need to reduce biofilm thickness and/or increase DO concentration will be limited to the first and possibly second stages where biomass growth rates and oxygen demand are highest. Variable speed drives may also have application in the latter stages of an RBC train where biofilm growth and oxygen demand are typically low as a technique for decreasing power consumption through reduced rotational speed.

Acceptable methods for achieving variable speed drive capability for RBC's include positive infinitely variable (P.I.V.) speed changers and variable frequency controllers, among others. P.I.V. speed changers are hand-adjusted



BEGGIATOA GROWTH

CLOSE-UP VIEW

Figure 3-11. First-stage Beggiatoa growth at Columbus, Indiana RBC plant (courtesy of City of Columbus).

units and work on the principal of changing mechanical gear ratios to obtain desired rotational velocity. Variable frequency controllers enable a.c. motor speed to be changed directly by varying the frequency of input current.

b. Supplemental Air

Supplemental air represents a second option for transitional correction of excess biofilm growth or low DO conditions in the lead stages of an RBC system. Supplemental air in a mechanical drive RBC plant should be used only when any of the above adverse conditions are encountered. Continuous use should be discouraged to avoid excessive power consumption.

3.4 Equipment Performance

3.4.1 Overall Structural and Mechanical Reliability

An EPA-sponsored survey and evaluation of design procedures for and process, operating and maintenance (O&M), equipment, and power performance of municipal RBC treatment facilities was conducted during the period September 1979 through November 1981 (7). A total of 36 plants was included in the survey. On-site visits and questionnaires were utilized to collect pertinent O&M and equipment-related data from 17 of the 36 plants. The structural and mechanical performance results of that survey are summarized in Table 3-2.

Equipment performance is separated in Table 3-2 into the three major component units of an RBC system:

1. Shaft - includes the horizontal support, bearing axles, and bearings. In the case of structurally supported media, the radial arms are also considered part of the shaft.

2. Media - the polyethylene sheets, formed into a variety of shapes whose surface supports the growth of a biological film. These sheets are either formed to support their own weight or are supported by steel arms radiating from a shaft.

3. Drive - includes the motor and the speed reduction system that connects it to the shaft. Speed reduction systems are composed of various combinations of multi-V-belt reducers, gear reducers, and chain-and-sproket reducers.

Some of the failures noted are endemic to any mechanical system; others are major and cannot be considered routine replacement. Only three of the 17

TABLE 3-2. STRUCTURAL AND MECHANICAL PERFORMANCE OF RBC PLANTS

Plant Location	No. of Shafts	No. of Years in Operation	Record of Failures: Shaft — No. of Failures	Shaft — Description	Shaft — Age at Failure (yr)	Shaft — Corrective Action	Media — No. of Failures	Media — Description	Media — Age at Failure (yr)	Media — Corrective Action	Drive — No. of Failures	Drive — Description	Drive — Age at Failure	Drive — Corrective Action
Rhinelander, Wisc.	10	3	2	Shaft break	2	Replace	---	---	---	---	---	---	---	---
Wappingers Falls, N.Y.	2	5	---	---	---	---	1	Media shifting	1	Repair (tighten)	5	Broken drive chain	1	Repair
Edgewater, N.J.	4	6	4	Radial arms deteriorating	1	Replace	4	Hub failures	1	Replace	---	---	---	---
Washington Twp., N.J.	3	4	3	Radial arms deteriorating	3	Replace	1	Slight media shifting	3	None as yet	---	---	---	---
Selden, N.Y.	12	5	4	Seized bearings	3 4	Repair (2) Replace (2)	1	Brittleness	4	None	---	---	---	---
Winchester, Ky.	4	4	2 2	Shaft break Worn bearings	2	Replace	---	---	---	---	---	---	---	---
Gloucester, N.J.	4	6	1 2	Shaft break Worn bearings	3 5	Replace Replace	---	---	---	---	---	---	---	---
Thermopolis, Wyo.	2	2	---	---	---	---	---	---	---	---	---	---	---	---
North Huntington, Pa.	4	5	3	Shaft break	4	Replace	---	---	---	---	---	---	---	---
Gladstone, Mich.	6	6	---	---	---	---	---	---	---	---	---	---	---	---
Cheboygan, Mich.	8	1	1	Shaft break	1	Replace	---	---	---	---	---	---	---	---
Ionia, Mich.	12	3	---	---	---	---	1	Media shifting	1	Brace	2	Broken drive chain	1	Replace
Hartford, Mich.	2	2	---	---	---	---	---	---	---	---	---	---	---	---
Vorhees, Twp. N.J.	6	2	2	Shaft break	1	Replace	6	Media breaking	1	Replace	---	---	---	---
Hamilton Twp., N.J.	48	1	1	Shaft break	1/2	Replace	---	---	---	---	---	---	---	---
Cleves, Ohio	6	3	---	---	---	---	---	---	---	---	---	---	---	---
Pewaukee, Wisc.	8	9	---	---	---	---	---	---	---	---	1 1	Electrical Drive chain	8 6	Repair Replace

Reproduced in part from Chesner and Iannone (7).

plants surveyed reported no failures with any of the three major component units.

3.4.1.1 Failures of the Shaft Component

The most serious equipment problem that can impact an RBC plant is shaft failures. A shaft failure involves a structural break in the horizontal member itself, the loss of the unit, and damage to a portion of the media. Repair requires that the damaged unit be removed and that a new shaft be installed along with salvaged and/or new media. Depending on the site layout, this may entail the removal of protective media covers or relocation of the entire shaft assembly outside a process building.

Shaft failures were reported for seven of the 17 plants listed in Table 3-2. None of the replacement shafts have experienced any failures to date. Of the 12 total shaft failures reported, all but one were located in the first stage of the respective treatment train, suggesting that excessive biofilm growth is contributing to overloadings of shaft carrying capability (7).

Another identified cause of shaft failures has been poor welding practice. The municipal RBC plant of the City of Columbus, Indiana, has experienced this type of failure (10). This plant, not included in Chesner and Iannone's survey (7), uses biodiscs for secondary treatment and nitrification and is the site of a cooperative RBC research project between EPA and the City.

The Columbus facility consists of 10 trains with eight shafts per train for a total of 80 shafts. The plant has experienced six shaft failures to date (September 1982), five in the first stage and one in the second stage. All six failures occurred at or near the same shaft location, approximately 20 ft from one end of the shaft. The cognizant RBC manufacturer investigated these failures and has attributed them to poor welding practice. In fabricating the shafts, 20-ft welding backup plates followed by additional 5-ft plates were used to span the 25-ft media segment of the shaft. The failures occurred at the juncture of the two plates in all six cases. The practice of employing discontinuous welding backup plates has since been terminated by the manufacturer in favor of uninterrupted 25-ft backup plates. Thus far, this welding procedural change has proven to be successful in eliminating shaft failures due to welding practice.

Bearings fail in RBC units when not properly maintained, when shaft deflections cause undue stress on the bearings, and when broken seals allow wastewater onto bearing surfaces eventually leading to corrosion. Replacement is performed with the shaft in place and is estimated to be a 2-day operation for two men (7). Eight bearings in three of the plants surveyed have been replaced as indicated in Table 3-2.

Radial arm media support systems are used by three of the five manufacturers currently marketing RBC's in the United States. These systems have undergone design modifications to improve their structural integrity. As shown in Table 3-2, two of the 17 plants surveyed have had to replace these support members.

3.4.1.2 Failures of the Media Component

As noted by Chesner and Iannone (7), media failures can occur directly due either to degradation of the HDPE from prolonged exposure to heat, concentrated organic solvents, or ultraviolet radiation or to breakage resulting from the excessive weight load of heavy biofilm growth. Plastic media can also suffer indirect or incidental breakage if the radial arm support system permits excessive media movement.

Six of the 17 RBC plants listed in Table 3-2 reported having had problems with the media component, including hub failures, shifting media, media brittleness, and media breakage from unspecified causes. Corrective action ranged from simple bracing to replacement of the entire media pack.

Media failures due to excessive shifting are being combated by the manufacturers by radial arm support system redesign and recommended inspection programs that specify more frequent tightening of the support rods. Ultraviolet rays in sunlight can lead to media brittleness. Precautions should be taken to avoid this problem either by adding anti-oxidatants to HDPE formulations or providing covers to shield the media from exposure to ultraviolet radiation.

Degradation from exposure to organic solvents is also an area where little difficulty should be expected or encountered. In a consultant report prepared for EPA, Landsberg (9) states that although HDPE is chemically inert to most wastewater ingredients, including dilute acids and bases, human wastes, household bleaches, detergents, soaps, and a large variety of concentrated acids and bases, certain aromatic hydrocarbons (organic solvents) such as toluene, methyl ethyl ketone, and gasoline have a deleterious effect on the material. He goes on to note, however, that lack of resistance of HDPE to aromatic hydrocarbons is not considered serious in municipal wastewater treatment since it would be rare for municipal wastewater to contain significant concentrations of these chemicals. Even when an occasional spill occurs, the concentration of the aromatic compounds would be diluted by the time they reached the plant and the contact period with any individual element of media sufficiently short so that no serious problems with HDPE degradation would be anticipated.

A serious and little understood cause of media failure is breakage due to stress cracking. Landsberg (9) reported that media failures from stress cracking have occurred as little as 6 to 9 mo following startup. Excerpts of his discussion relative to this problem area are presented below.

Stress cracking is an internal or external rupture in the plastic caused by tensile stresses of lesser magnitude than the short-term mechanical strength of the material. Although the exact cause is not known, the suspected mechanism involves propagation of a crack through the weak chemical bonds of the material. The weakest link of high density crystalline polyethylene is along the crystallite or sperulite boundaries. Any conditions leading to stress and strain along these boundaries would lead to lower stress crack resistance. Stress cracking is highly dependent on the nature and level of the applied stress and most readily occurs under the influence of high multi-axial stressing. If, in addition to this type of stressing, a hostile environment is encountered, the rate and severity of the stress cracking are magnified. Landsberg (9) notes that the literature indicates that HDPE can withstand many chemicals when not under stress, but that under stress the same materials have a severe deleterious effect.

In RBC units, multi-axial stressing occurs to an appreciable extent. First, the RBC media is rotating slowly. Second, as the biofilm increases in weight, the polyethylene is subjected to increased loads, which result in added stressing. Finally, with some units, a number of media packs are bolted together, which generates stresses in a plane perpendicular to the direction of rotation. The various methods of attaching the plastic media to the shaft determine the stresses imposed on the media and should be taken into consideration when estimating expected media life.

Another factor that should be considered in evaluating the expected life of RBC media is the difference of the coefficients of expansion of HDPE and steel. Steel has a coefficient of expansion of approximately 6-8 in./in./^{o}C x 10^{-6}, whereas the plastic has a coefficient of expansion of 1.3 in./in./^{o}C x 10^{-4}. This difference in the coefficients of expansion can lead to problems when the plastic components are in direct contact with the metal shaft and support arm structures.

In summary, the integrated media-shaft units form a rather complex mechanical system whose expected life depends not only on the properties of the plastic components and the shaft carrying capability, but also on the structural integrity of the radial arm media support system (Clow, Crane-Cochrane, and Lyco) or the interaction of the shaft and media at their interface (Autotrol and Walker Process). All of these factors should be assessed and taken into account in comparing the expected life cycles and cost effectiveness of RBC equipment.

3.4.1.3 Failures of the Drive Component

According to Chesner and Iannone (7), the drive assembly is the most reliable component of a mechanical drive RBC system. Only three of 17 plants surveyed reported problems with mechanical drives (Table 3-2), and these were minor. Operating experience with air drive systems is too limited to date to make definitive projections of equipment performance. The more critical aspects of air drive performance would appear to be air distribution to multiple shafts and maintaining uniform rotational speed rather than reliability of the air delivery equipment. Lack of positive rotational control with air drive systems has become severe enough in several cases to completely stop rotation.

3.5 Evaluation of Shaft Design Procedures

The wide variation in shaft design procedures has aroused considerable concern as to the adequacy of RBC shafts to provide 20 or more yr of reliable service. This concern was precipitated first by reported shaft failures at industrial wastewater treatment installations followed by similar observations at several municipal RBC facilities. As indicated in Section 3.4.1.1, most of the reported shaft failures to date have been associated with the lead stages of RBC trains where the heaviest biofilm growths are normally encountered.

Assuming satisfactory welding practice, the most likely cause of shaft failure is fatigue. Under EPA sponsorship, Drs. R. M. Bowman and J. T. Gaunt of Purdue University, were retained to 1) examine the various fatigue design techniques employed by the manufacturers of RBC shafts, 2) recommend a preferred code or design technique, and 3) conduct a fatigue behavior evaluation for various shaft cross-sectional shapes representative of those used by the several manufacturers. Pertinent excerpts from their report (11) are given below.

3.5.1 Design Criteria and Codes

3.5.1.1 General Considerations

Most building and bridge design codes for structural steel use a similar design methodology to account for fatigue resistance. Extensive experimental testing of laboratory specimens has shown that the logarithm of fatigue life, N, is linearly related to the logarithm of the range of applied stress, S_R, between certain limits of the cyclic life, as shown in Figure 3-12 for Categories A and B of the American Welding Society (AWS) Structural Welding Code (12) for Design of Tubular Structures (Section 10) and Category C of the AWS Welding Code (12) for Design of New Bridges (Section 9). The stress range at which a curve becomes flat is known as the fatigue (or endurance) limit and represents the value of the applied stress range for which no appreciable fatigue damage occurs under atmospheric conditions. A member subjected to rotating/cyclic loads with a maximum corresponding stress range less than the fatigue limit will not fail (within a certain high level of confidence) under these conditions.

Geometry, detailing, and fabrication quality can each have a significant effect on the fatigue resistance of a member. Transverse or longitudinal welding,

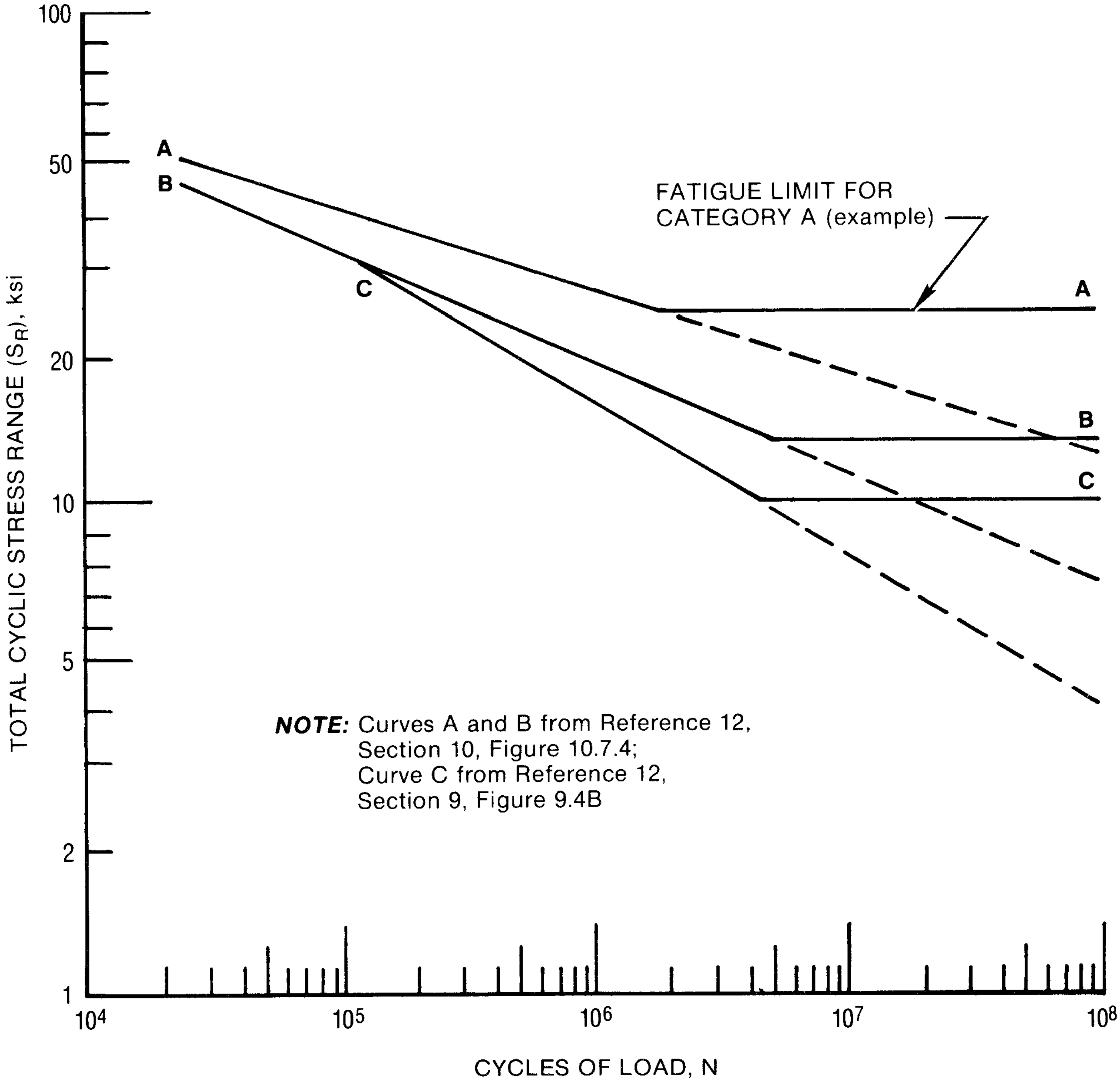


Figure 3-12. Allowable fatigue stress ranges for three stress categories of redundant structures in atmospheric service.

welded attachments, bolting, and weld toe treatment are geometrical factors that influence fatigue behavior. Since structural detailing and weld fabrication quality can affect fatigue behavior, the weldment fabrication provisions of the AWS Structural Welding Code (12) should be adopted as an absolute minimum requirement. Sketches of appropriate joint details and fabrication provisions are fully treated in Reference 12.

The particular S-N curve that describes the fatigue resistance of a given member or detail must be used to properly design for fluctuating loads. To conservatively account for the inherent scatter of fatigue data, a lower confidence level curve, usually 95 percent, is generally used to describe fatigue resistance instead of the best-fit S-N curve.

Obviously, it is very important to select the S-N curve that best describes the structural member being designed. If a family of S-N curves from a particular code is utilized in designing for fatigue, in lieu of costly definition of an S-N curve from exhaustive experimental laboratory testing, careful subjective judgement must be exercised in selecting the appropriate S-N curve.

3.5.1.2 Fatigue Design Provisions

Fatigue provisions of various design codes used to proportion tubular members are not all similar. The fatigue provisions of the AWS (12) Section 10 (Tubular Structures) and Section 9 (New Bridges), American Association of State Highway and Transportation Officials (AASHTO) (13), American Institute of Steel Construction (AISC) (14), and American Railway Engineering Association (AREA) (15) codes were considered herein for RBC shaft design. Most of the AISC, AREA, and AWS (New Bridges) fatigue provisions, however, are based on the AASHTO fatigue requirements. Further, since the AWS (New Bridges) fatigue provisions are identical to the AASHTO fatigue requirements, in-depth code evaluation was limited to a detail-by-detail comparison of the fatigue design provisions of the AWS Section 10 (Tubular Structures) and AWS Section 9 (New Bridges) codes. Only typical RBC structural details were considered.

Although an RBC shaft is a non-redundant system, failure would not likely result in loss of life. Therefore, AWS fatigue provisions for redundant load path structures were utilized in this comparative design evaluation of RBC shafts. These provisions are believed to be more representative of actual shaft fatigue behavior.

a. Plain Unwelded Tubes

The fatigue resistance of plain unwelded tubes is dictated primarily by tube geometry. For tubes without sharp corners or notches, the use of the S-N curve for circular tubes given by AWS (Tubular Structures) Category A (see Figure 3-12) is recommended for fatigue-resistant shaft design.

b. Tubes with Longitudinal Weld Seams

The fatigue resistance of tubes with longitudinal weld seams or continuously welded longitudinal attachments is governed by tube geometry and weld location. For welds placed in the flat portions of rectangular or octagonal tubes, the use of the S-N curve for circular sections given by AWS (Tubular Structures) Category B (see Figure 3-12) is recommended for fatigue-resistant shaft design.

c. Tubes with Transverse Weld Attachments

The fatigue resistance of tubes with transverse weld attachments is governed primarily by the attachment detail. The fatigue provisions of the AWS (Tubular Structures) and AWS (New Bridges) design codes for transverse weld attachments are significantly different. The S-N curves for AWS (Tubular Structures) Category C_2, transverse ring stiffeners, and Category D, miscellaneous attachments, are notably lower than the S-N curve for AWS (New Bridges) Category C, welded attachments with detail dimension parallel to the direction of stress less than 2-in. The use of the S-N curve given by AWS (New Bridges) Category C (see Figure 3-12) is recommended for fatigue-resistant shaft design in this case, based primarily on the background and supporting data for the three curves.

AWS (Tubular Structures) Categories C_2 and D are limited to situations in which nominal member stresses represent actual load transfer across the weld (16). The loads on RBC shafts, however, are transferred in-plane through the welds, rather than out-of-plane across the attachment welds.

AWS (New Bridges) Category C, on the other hand, is intended for situations in which the attachment is used to transfer in-plane loads or to stiffen the cross-section. The position and endurance limit of the S-N curve for AWS (New Bridges) Category C are based on numerous laboratory fatigue tests reported in Reference 17 for steel beams with welded transverse attachment lengths less than 2 in. parallel to the direction of stress. The AWS (New Bridges) Category C endurance limit is also consistent with recent fatigue data reported for transverse welded attachments on A588 steel beams (18).

d. Tubes with Bolted Attachments

Little direction is available for tubes with bolted attachments. AWS (Tubular Structures) Category B represents a reasonable lower bound for fatigue data reported by Stallmeyer (19), Osman (20), and Wilson et al. (21) for plain plate mild steel specimens containing a central circular notch. Therefore, the use of the S-N curve given by AWS (Tubular Structures) Category B (see Figure 3-12) is recommended for fatigue-resistant design of shaft tubes with bolted attachments.

3.5.1.3 Service Conditions

The curves A, B, and C in Figure 3-12 are basic guidelines for shaft design based on structural detail. Two extraneous conditions may alter these curves.

Under constant cycle loading, a fatigue limit (crack growth threshhold) exists for any given shaft. Three fatigue limits are illustrated in Figure 3-12 by the horizontal portions of Curves A, B, and C. This is not the condition under variable random loadings where the evidence is that the S-N relationship continues to extend into the lower stress range regions.

The effects of corrosion would also tend to devalue fatigue limits. Obviously, the extent of devaluation would depend on the severity of the environment.

For random variable (wave action) loadings and a sea water environment, the American Petroleum Institute (API) (22) has suggested extending S-N curves for fixed offshore platforms at the same slope (similarly to the extended dashed portions of curves A, B, and C in Figure 3-12), with no fatigue limits in the region of those cycle numbers representing the expected life of RBC systems (20 yr).

RBC shafts typically are not subjected to random variable loadings, as defined by API (22), during operation. Regardless of the structural detail category of the shaft, it is essential that imposition of random variable loadings also be avoided during maintenance activities.

The RBC manufacturers recognize that shafts must be protected from possible loss of fatigue strength due to the corrosive effects of wastewater. Epoxy coatings are routinely used by the manufacturers to protect shafts from potential corrosion. Available information from coating manufacturers indicates that epoxy coating materials have an expected life of from 5 to over 10 yr, although long-term field data are limited. In selecting or specifying RBC shafts, the designer should require evidence from the shaft manufacturer that satisfactory fatigue stress protection, including protection from possible corrosive effects, has been provided for the design life of the system under expected loading and environmental conditions.

After consideration of the protection offered by an epoxy coating, the designer may feel that a depression or lowering of a particular fatigue limit associated with curve A, B, or C in Figure 3-12 is warranted or that the stress curve should be extended below the fatigue limit at some intermediate slope. There is no compelling evidence to indicate, however, that the allowable stress for an RBC shaft operating in municipal wastewater would need to be lowered to the degree obtained from the extended dashed lines in Figure 3-12.

3.5.1.4 Summary of Stress Category Recommendations

The stress categories recommended for fatigue-resistant design of RBC shafts are summarized in Table 3-3. One design code, AWS, can be utilized by specifying the S-N curve appropriate for a given RBC shaft detail.

3.5.2 Estimated Shaft Fatigue Performance

3.5.2.1 Design Parameters

The expected fatigue lives for various shaft geometric cross-sections were estimated based on the recommended fatigue stress categories summarized in Table 3-3. Once the design stress for a given cross-section was determined, the range of applied alternating stress resulting from shaft rotation was used in conjunction with the design stress category (Table 3-3) to estimate the corresponding fatigue life. Each rotation of the shaft represents one loading cycle, and the fatigue life equals the number of loading cycles until failure. Geometric shapes evaluated included a 30-in. diameter circular shaft, a 16-in. diameter circular shaft, a 16-in. square shaft, and a 24-in. octagonal shaft. A number of shaft wall thicknesses were considered for each geometric cross-section.

Stress analysis of each shaft section was conducted using consistent design criteria. The 12-ft diameter plastic media were assumed to be 40 percent submerged in wastewater. Both standard density RBC media (100,000 sq ft surface area/27-ft shaft length) and high density RBC media (150,000 sq ft surface area/27-ft shaft length) were considered with uniform attached slime thicknesses ranging in 25-mil (0.025-in.) increments from clean media to 150 mils (0.15 in.). The specific gravity of the attached biomass was assumed to be 1.0.

A typical 27-ft long shaft was assumed to be simply supported with a 26.5-ft span length from centerline to centerline of the bearings. The maximum bending moment was computed assuming that 1) a hub weight of 200 lb was positioned 6 in. from the center of the support, 2) a uniform shaft weight acted along the entire span length, and 3) a uniform effective media weight acted along the middle 25 ft of the shaft. The uniform effective media weight was computed on the basis of 60 percent of the combined uniform total media and attached slime weights to account for the impact of buoyancy. A total media weight (neglecting buoyancy) of 10,000 lb was assumed for standard density RBC media, while a weight of 15,000 lb was assumed for high density RBC media. Total media weight includes the plastic media weight and media superstructure support weight.

TABLE 3-3. RECOMMENDED STRESS CATEGORIES FOR RBC TUBULAR SHAFTS

RBC Stress Category	Type of Shaft Design	Corresponding Stress Category from Design Standards (Atmospheric Conditions) AWS(TS)*	AWS(NB)†
I	Plain unwelded tubes	A	-
II	Tubes with longitudinal seam and/or continuously welded longitudinal stiffeners	B	-
III	Tubes with transverse ring stiffeners or miscellaneous attachments fastened by fillet welds with length in direction of stress less than 2 in.	-	C
IV	Tubes with miscellaneous attachments fastened by bolting or tapping	B	-

* Fatigue provisions in Section 10 (Design of Tubular Structures) of Reference 12.
† Fatigue provisions in Section 9 (Design of New Bridges) of Reference 12.

The maximum bending stress for a given shaft cross-section was computed by dividing the maximum bending moment by the corresponding section modulus. Because an RBC shaft is subjected to both tension and compression during each rotational cycle, the stress range was then obtained by doubling the maximum bending stress. Maximum principal stresses were not utilized since torsional shearing stresses for the closed sections were very small.

3.5.2.2 Matrix of Estimated Shaft Lives

Estimated shaft fatigue lives for the several cross-sectional shapes investigated are summarized in Tables 3-4 to 3-7 as a function of detail category, structural shape thickness, media density, and attached biological slime thickness. Loadings in which the resulting range of applied stress is less than the endurance (fatigue) limit are denoted in the tables as FL. As noted earlier, a member subjected to an applied stress range below the fatigue

TABLE 3-4. ESTIMATED FATIGUE LIFE FOR 30-IN. DIAMETER CIRCULAR SHAFT

Standard Density Media

Detail Category	Structural Shape Thickness (in.)	Estimated Life (yr) at Indicated Slime Thickness (mils)*						
		0	25	50	75	100	125	150
II	0.500	FL†	FL	FL	FL	FL	FL	5.0
	0.625	FL	FL	FL	FL	FL	FL	FL
	0.750‡	FL	FL	FL	FL	FL	FL	FL
	0.875	FL	FL	FL	FL	FL	FL	FL
III	0.500	FL	FL	FL	FL	5.1	2.8	1.7
	0.625**	FL	FL	FL	FL	FL	5.4	3.3
	0.750††	FL	FL	FL	FL	FL	FL	5.6
	0.875	FL	FL	FL	FL	FL	FL	FL

High Density Media

Detail Category	Structural Shape Thickness (in.)	Estimated Life (yr) at Indicated Slime Thickness (mils)*						
		0	25	50	75	100	125	150
II	0.500	FL†	FL	FL	FL	3.9	1.7	0.9
	0.625	FL	FL	FL	FL	FL	4.3	2.2
	0.750‡	FL	FL	FL	FL	FL	FL	4.5
	0.875	FL	FL	FL	FL	FL	FL	FL
III	0.500	FL	FL	FL	3.0	1.5	0.8	0.5
	0.625**	FL	FL	FL	FL	2.8	1.5	0.9
	0.750††	FL	FL	FL	FL	4.7	2.6	1.6
	0.875	FL	FL	FL	FL	FL	4.0	2.5

* 1 mil = 0.001 in.
† FL = fatigue limit
‡ Walker Process
** Clow
†† Crane-Cochrane

TABLE 3-5. EXPECTED FATIGUE LIFE FOR 28-IN. DIAMETER CIRCULAR SHAFT

Standard Density Media

Detail Category	Structural Shape Thickness (in.)	Estimated Life (yr) at Indicated Slime Thickness (mils)*						
		0	25	50	75	100	125	150
II	0.500	FL†	FL	FL	FL	FL	4.41	2.24
	0.625	FL	FL	FL	FL	FL	FL	FL
	0.750‡	FL	FL	FL	FL	FL	FL	FL
	0.875	FL	FL	FL	FL	FL	FL	FL
III	0.500	FL	FL	FL	FL	2.71	1.51	0.91
	0.625	FL	FL	FL	FL	FL	2.87	1.76
	0.750	FL	FL	FL	FL	FL	FL	2.95
	0.875	FL	FL	FL	FL	FL	FL	4.50

High Density Media

Detail Category	Structural Shape Thickness (in.)	Estimated Life (yr) at Indicated Slime Thickness (mils)*						
		0	25	50	75	100	125	150
II	0.500	FL	FL	FL	4.81	1.77	0.78	0.39
	0.625	FL	FL	FL	FL	4.31	1.92	0.97
	0.750‡	FL	FL	FL	FL	FL	3.92	1.99
	0.875	FL	FL	FL	FL	FL	FL	3.61
III	0.500	FL	FL	4.13	1.61	0.77	0.42	0.25
	0.625	FL	FL	FL	3.06	1.48	0.82	0.49
	0.750	FL	FL	FL	FL	2.49	1.38	0.84
	0.875	FL	FL	FL	FL	3.81	2.13	1.30

* 1 mil = 0.001 in.
† FL = fatigue limit
‡ Lyco Series 300

TABLE 3-6. ESTIMATED FATIGUE LIFE FOR 16-IN. SQUARE SHAFT

Standard Density Media

Detail Category	Structural Shape Thickness (in.)	Estimated Life (yr) at Indicated Slime Thickness (mils)*						
		0	25	50	75	100	125	150
I	0.875	FL†	FL	FL	FL	FL	FL	2.4
	1.00	FL	FL	FL	FL	FL	FL	FL
	1.125	FL	FL	FL	FL	FL	FL	FL
II	0.875	FL	FL	FL	FL	5.6	2.5	1.3
	1.00‡	FL	FL	FL	FL	FL	4.0	2.0
	1.125	FL	FL	FL	FL	FL	5.8	3.0

High Density Media

Detail Category	Structural Shape Thickness (in.)	Estimated Life (yr) at Indicated Slime Thickness (mils)*						
		0	25	50	75	100	125	150
I	0.875	FL†	FL	FL	FL	1.7	0.6	0.2
	1.00	FL	FL	FL	FL	FL	1.1	0.4
	1.125	FL	FL	FL	FL	FL	1.8	0.7
II	0.875	FL	FL	FL	2.8	1.0	0.5	0.2
	1.00‡	FL	FL	FL	4.3	1.6	0.7	0.4
	1.125	FL	FL	FL	6.3	2.4	1.1	0.5

* 1 mil = 0.001 in.
† FL = fatigue limit
‡ Autotrol

TABLE 3-7. ESTIMATED FATIGUE LIFE FOR 24-IN. OCTAGONAL SHAFT

Standard Density Media								
Detail Category	Structural Shape Thickness (in.)	Estimated Life (yr) at Indicated Slime Thickness (mils)*						
		0	25	50	75	100	125	150
II	0.625	FL†	FL	FL	FL	FL	5.0	2.6
	0.750‡	FL	FL	FL	FL	FL	FL	5.1
	0.875	FL	FL	FL	FL	FL	FL	FL
III	0.625	FL	FL	FL	FL	3.1	1.7	1.1
	0.750	FL	FL	FL	FL	5.1	2.9	1.8
	0.875	FL	FL	FL	FL	FL	4.3	2.7

High Density Media								
Detail Category	Structural Shape Thickness (in.)	Estimated Life (yr) at Indicated Slime thickness (mils)*						
		0	25	50	75	100	125	150
II	0.625	FL†	FL	FL	5.5	2.0	0.9	0.5
	0.750‡	FL	FL	FL	FL	4.1	1.8	0.9
	0.875	FL	FL	FL	FL	FL	3.3	1.7
III	0.625	FL	FL	4.7	1.8	0.9	0.5	0.3
	0.750	FL	FL	FL	3.1	1.5	0.8	0.5
	0.875	FL	FL	FL	4.6	2.3	1.3	0.8

* 1 mil = 0.001 in.
† FL = fatigue limit
‡ Lyco/Hormel Series 200

limit will not fail (with a high level of confidence) as a result of structural fatigue.

The estimated shaft lives presented in Tables 3-4 to 3-7 were calculated based on an assumed rotational speed of 1.6 rpm or 840,000 revolutions/yr, representative of a typical mechanical drive RBC unit. A shaft rotating at 1.2 rpm or 630,000 revolutions/yr, more representative of an air drive RBC unit, would have an extended estimated life of 1.6/1.2 = 1.33 times that projected for the same shaft design operating at 1.6 rpm.

Examination of these tables indicates that a shaft equipped with high density media would be expected to reach its fatigue or endurance limit at a lower biofilm thickness than the same shaft operating with standard density media. This difference is attributable, of course, to the nominal 50 percent higher specific surface area of high density media. Accordingly, high density media should not be specified for use in the early stages of an RBC train, with the possible exceptions of Walker Process and Lyco whose shafts are projected to have fatigue limits equal to or greater than those loads resulting from biofilm 125 mils (0.125 in.) and 100 mils (0.1 in.) thick, respectively, on high density media. Of the other three current shaft designs, all are estimated to have satisfactory fatigue resistance with high density media up to slime thicknesses of at least 50 mils (0.05 in.) and two up to at least 75 mils (0.075 in.). Based on these estimates, a conservative upper biofilm thickness limit of 50 mils (0.05 in.) is recommended for high density media, with the exceptions of Walker Process and Lyco as stated before.

High density media has been used advantageously in the middle and latter stages of RBC trains where decreased availability of organic carbon and the frequent occurrence of nitrification combine to produce biofilms characteristically less than 50 mil (0.05 in.) thick. A recommended general practice, subject to site specific adjustment, is not to employ high density media before the third stage of a sequentially-staged RBC module.

Current manufacturer shaft designs used in conjunction with standard density media are projected (Tables 3-4 to 3-7) to be resistant to failure from fatigue at slime thicknesses ranging from at least 75 mils (0.075 in.) to 150 mils (0.15 in.) or greater. Again, the Walker Process and Lyco designs are estimated to have higher load carrying capabilities than the other three shafts. Allowing for exceptions based on engineering judgement and the use of higher load capacity equipment, it is recommended that when biofilm thickness on standard density media reaches 75 mils (0.075 in.), corrective action be initiated to maintain an adequate safety margin against shaft overstressing. In some instances, biofilm growth in the initial stages (primarily stages 1 and 2) may naturally equilibrate at thicknesses greater than 75 mils (0.075 in.). Depending on the particular shaft design being used, it may then become critical for the plant operator to implement contingency procedures to either 1) shear biomass from the media through temporarily-increased rotational speed or supplemental air stripping as discussed in Section 3.3.5.2 or 2) reduce the organic loading to the affected stage(s) by step feeding part of the incoming flow to other stages or removing stage-separation baffles to modify load distribution. Although standard density media can be and has been specified for an entire RBC facility, their most beneficial usage today is in the lead stages of an RBC train. Not only can shafts outfitted with standard density media better tolerate the higher biofilm thicknesses encountered there, but DO deficiencies are less likely to occur. The higher volumetric concentration and accompanying higher overall demand for oxygen of biomass growing on high density media could more readily exceed the oxygen transfer capacity of media operating in the first two stages.

3.5.3 Summary of Conclusions

In summarizing their report, Bowman and Gaunt (11) reiterated the following major conclusions of their analysis of fatigue design criteria for RBC shafts:

1. Shafts should be proportioned in accordance with the fatigue design stress categories presented in Table 3-3.
2. Use of appropriate fatigue provisions of the AWS Structural Welding Code will provide for adequate fatigue-resistant shaft design.
3. Shaft structural detail will dictate whether fatigue provisions of the AWS Structural Welding Code from the section on Design of Tubular Structures or the section on Design of New Bridges should be used.
4. Weld fabrication quality should satisfy the provisions of the AWS Structural Welding Code as an absolute minimum requirement.
5. A matrix of estimated shaft fatigue lives is presented in Tables 3-4 to 3-7 as a function of biofilm thickness for the several shaft geometric cross-sections evaluated.
6. The above estimates of shaft fatigue life assume no shaft deterioration due to corrosion.

3.6 References

1. Autotrol Wastewater Treatment Systems Design Manual. Autotrol Corporation, Bio-Systems Division, Milwaukee, Wisconsin, 1978.
2. Clow Envirodisc Rotating Biological Contactor Systems Catalog. Clow Corporation, Florence, Kentucky, 1980.

3. Crane-Cochrane Rotating Biological Contactor Brochure. Crane Company, Cochrane Environmental Systems, King of Prussia, Pennsylvania, 1981.

4. Lyco Wastewater Products - RBS Systems Catalog. Lyco Division of Remsco Associates, Marlboro, New Jersey, 1982.

5. RBC systems brochure from Manufacturer X, 1978.

6. Walker Process BioSpiral Rotating Biological Contactors Brochure. Walker Process Corporation, Aurora, Illinois, 1979.

7. Chesner, W. H. and J. Iannone. Review of Current RBC Performance and Design Procedures. Report prepared for USEPA, Municipal Environmental Research Laboratory, Cincinnati, Ohio, under Contract No. 68-02-2775 by Roy F. Weston, Inc., (Publication pending).

8. Personal communication from R. W. Hankes, Crane Company, Cochrane Environmental Systems, King of Prussia, Pennsylvania, to R. C. Brenner, USEPA, Cincinnati, Ohio, August 25, 1982.

9. Landsberg, M. I. Rotating Biological Surface Waste Water Treatment Units. Internal report prepared for USEPA under consultant agreement, Cincinnati, Ohio, August 1981.

10. Opatken, E. J. Personal observations at Columbus, Indiana RBC plant during field monitoring of cooperative research and development project. USEPA Cooperative Agreement No. CR807463, 1981.

11. Bowman, M. D. and J. T. Gaunt. Fatigue Behavior of Rotating Biological Contactor Shafts. Internal report prepared for USEPA under Purchase Order No. C2159NAST, Cincinnati, Ohio, April 1982.

12. American Welding Society. Structural Welding Code-Steel. 5th Edition, ANSI/AWS D1.1-81, 1981.

13. American Association of State Highway and Transportation Officials. Standard Specifications for Highway Bridges. 12th Edition, 1977.

14. American Institute of Steel Construction. Specifications for the Design, Fabrication, and Erection of Structural Steel for Buildings. 1978.

15. American Railway Engineering Association. Specifications for Steel Railway Bridges. 1981.

16. Marshall, P. W. and A. A. Torpac. Basis for Tubular Joint Design. Welding Journal, 53(5):192s-201s, May 1974.

17. Fisher, J. W., P. A. Albrecht, B. T. Yen, D. J. Klingerman, and B. M. McNamee. Fatigue Strength of Steel Beams with Welded Stiffeners and Attachments. National Cooperative Highway Research Program Report No. 147, 1974.

18. Friedland, I. M., P. A. Albrecht, and G. R. Irwin. Fatigue of Two Year Weathered A588 Stiffeners and Attachments. Journal of the Structural Division, ASCE, 108(ST1):125-144, January 1982.

19. Stallmeyer, J. E. The Effect of Stress History on Cumulative Damage in Fatigue. Ph.D. Dissertation, University of Illinois at Champaign-Urbana, 1953.

20. Osman, H. A. Evaluation of Local Plastic Strain History in Fatigue. Ph.D. Dissertation, University of Illinois at Champaign-Urbana, 1966.

21. Wilson, W. M. and F. P. Thomas. Fatigue Tests of Riveted Joints. Engineering Experiment Station Bulletin No. 302, University of Illinois at Champaign-Urbana, May 1938.

22. American Petroleum Institute. API Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms. 12th Edition, API RP 2A, January 1981.

SECTION 4

POWER CONSUMPTION

4.1 Introduction

Power consumption in mechanically driven systems results from the power used to overcome internal resistances and losses in the motor, friction losses in gear reduction and drive belts or chains, friction losses in shaft support bearings, and the drag forces resulting from rotation of the media and attached biofilm through the wastewater. The drag forces are affected by the amount of media surface area, the shape of that surface area, rotational speed, wastewater viscosity, and the type and amount of biological growth. Since each manufacturer uses media with somewhat different shapes and different media support structures or orientation of media openings, some variation in power requirements among the various units can reasonably be expected.

With air driven systems, compressed air is discharged beneath the RBC media as shown in Section 3. The rising air is captured by the air cups, and the resulting buoyant forces provide the torque necessary for media rotation. Power is required in air driven systems for losses in the motor, compressor, air headers, control valves, and diffusers and also to overcome the static head of wastewater in the RBC tank.

4.2 Fundamentals

Power measurements from a number of mechanically and air driven RBC plants are presented later in this section. Before these data are reviewed, it is appropriate to set forth some fundamental considerations related to power measurement and power consumption for those who may not be familiar with this information.

Several basic alternatives must be considered in the design of any power distribution system. The relatively high cost of electrical power today is placing additional pressures on the designer to make power distribution systems as energy efficient as possible. Induction motors constitute the major power demands in most wastewater treatment plants and are available at different operating voltages; the most common operating voltages are

120, 208, 240, 480, and 600 volts. Induction motors are also available for single-phase or polyphase service.

The selection of the operating voltage of an induction motor is an important decision. As the operating voltage increases, the current decreases, which directly reduces the line losses in the system and permits the use of smaller conductors. Comparative information for various 7.5-hp motor options is presented in Table 4-1. The full-load current for single-phase operation is significantly higher than for the three-phase options with commensurately higher wire costs. A substantial difference in wire cost is also apparent between three-phase, 240- and 480-volt operation, but the difference between the three-phase, 480- and 600-volt options is less significant. Based on capital and operating costs, three-phase, 480-volt operation is the industry standard.

For a balanced Y or Δ circuit, the actual power, kW, being drawn by a three-phase motor is computed by the equation given below:

$$kW = \sqrt{3}\ EI\ (\cos \theta/1000) \qquad (4\text{-}1)$$

where kW is the kilowatts drawn, E is the line voltage, I is the current in amperes, and θ is the phase angle between the voltage and the current.

The apparent power, kVA, for the same motor is given by:

$$kVA = \sqrt{3}\ (EI/1000) \qquad (4\text{-}2)$$

TABLE 4-1. COMPARISON OF FULL-LOAD CURRENT, MINIMUM COPPER WIRE SIZE, AND WIRE COSTS FOR VARIOUS 7.5-HP MOTOR OPTIONS

No. of Phases	EMF (volts)	Full-Load Current (amps)	Minimum Copper Wire Size (AWG)	Representative Wire Cost* ($/1000 ft)
1	120	80	1	437.90
1	240	40	6	198.27
3	240	28	8	130.73
3	480	14	12	51.29
3	600	11	14	37.24

* Wire costs are based on 7-strand THW.

The power factor, cos θ, can then be calculated as:

$$\text{Power Factor} = \frac{\text{Actual Power}}{\text{Apparent Power}} \quad (4\text{-}3)$$

The power factor can also be read directly by using a power factor meter. It is important to recognize that the polyphase wattmeters used to meter power consumption measure actual power, kW, drawn, but that demand charges are based on apparent power, kVA. A power factor less than 0.9 will result in higher power bills because of increased demand charges, and many electric utilities have penalty charges for customers with low power factors.

Low power factors result from the operation of equipment with inductive loads that require reactive power. Reactive power, kvar, is essentially lost in the system and, consequently, is synonymous with higher power costs. The power factor of an induction motor decreases, increasing the relative kVAR, as the load decreases. Additionally, the efficiency of an induction motor decreases as the load decreases. The variations in both power factor and efficiency as a function of load are shown in Table 4-2. It is clear that the needless oversizing of electric motors is costly both in terms of capital and operating expenses.

When uncorrected, the power factors at wastewater treatment plants are usually low, typically ranging from 0.4 to 0.7. Most electric utilities have demand charge schedules that penalize customers with power factors less than 0.9; therefore, power factor correction can be a very important factor in reducing operating costs at wastewater treatment plants.

Field investigations were made on one train each at the LeSourdsville and Upper Mill Creek (Butler County, Ohio) RBC treatment plants. Both plants

TABLE 4-2. CHANGE IN POWER FACTOR AND MOTOR EFFICIENCY AS A FUNCTION OF LOAD FOR 7.5-HP POLYPHASE INDUCTION MOTOR

Percent of Full-Load	Power Factor	Efficiency (percent)
25	0.37	72.0
50	0.70	86.7
75	0.78	87.9
100	0.82	87.7

employ mechanically driven RBC units equipped with power factor correction capacitors, which permitted measurement of both the uncorrected and corrected power factors. These data and other pertinent information for LeSourdsville and Upper Mill Creek are presented in Tables 4-3 and 4-4, respectively. The last column in both tables is the difference in apparent power, kVA, before and after power factor correction. Typically, a 2.5-kVA reduction in apparent power was noted at both plants as a result of power factor correction. However, the data obviously indicate that additional power factor correction would be beneficial for the LeSourdsville plant.

Assuming demand charges of $6.92/month/kVA, power factor correction in the range illustrated in Tables 4-3 and 4-4 will reduce monthly operating costs $15 to $20 per shaft. Typical list prices (third quarter 1982) for 1-, 2-, and 5-kvar capacitors are $94, $99, and $143, respectively. Based on an approximate installation cost of $100, the payout period for a 2.5-kVA power factor correction is about 12 months. Depending on the original power factor and the degree of correction possible, the payout period could vary from a few months to several years.

Significant variation was observed in both current draw and power factor at both plants. The variability was attributed to out-of-balance shafts due to uneven biofilm growth. The required power increased as the heavier segment of the RBC rotated to the top of the arc and decreased significantly as the heavier section rotated to the bottom.

Other factors directly affect the power consumed to operate mechanical drive RBC installations. If properly maintained, the drive train, consisting of gear reducers, chains and sprockets, and V-belts and pulleys, can be reasonably efficient. A good quality gear reduction unit should have an efficiency of 95 to 97 percent, and a chain-and-sprocket drive should be about 95 percent efficient, provided neither the chain nor sprockets are badly worn. A V-belt drive with new, matched belts and with proper tension will have an efficiency of 93 to 94 percent. Under optimum conditions, therefore, the drive train should operate at approximately 86 percent efficiency with respect to power transmission. If appreciable wear occurs in any of the three components, efficiency will decrease with the V-belt drives being most susceptible to wear.

4.3 Air Drive Systems

4.3.1 Basic Relationships

Air driven RBC's are proprietary systems manufactured by the Autotrol Corporation. A typical air driven RBC unit contains 24 longitudinal rows of inverted air trays with 11.5 trays per row attached around the periphery of the media. Each tray is 2-ft long by 14-in. wide and is partitioned

TABLE 4-3. RESULTS OF RBC MECHANICAL DRIVE POWER MEASUREMENTS AT THE LESOURDSVILLE WASTEWATER TREATMENT PLANT, BUTLER COUNTY, OHIO

		Field Measurements at Motor Disconnect					Measurements at Motor Starter with Power Factor Correction*					
Drive No.†	Rotational Speed (rpm)	EMF (volts)	Current (amps)	Power Factor	Apparent Power (kVA)	Actual Power (kW)	EMF (volts)	Current (amps)	Power Factor	Apparent Power (kVA)	Actual Power (kW)	Difference in Apparent Power (kVA)
11	1.52	476	9.5 - 9.7	<0.1 - 0.33	7.91	<1.70	478	5.9 - 6.3	0.15 - 0.41	5.05	1.41	2.86
12	1.68	476	5.4 - 6.3	0.18 - 0.50	4.82	1.64	478	2.5 - 3.7	0.45 - 0.74	2.57	1.53	2.25
13	1.63	476	5.2 - 8.8	0.12 - 0.64	5.77	2.19	478	2.2 - 5.9	0.26 - 0.84	3.35	1.84	2.42
14	1.61	476	6.8 -10.0	0.23 - 0.66	6.93	3.08	478	4.3 - 8.3	0.31 - 0.77	5.22	2.82	1.71
15	1.52	476	9.2 - 9.5	0.34 - 0.40	7.71	2.85	478	9.4 - 9.7	0.33 - 0.37	7.91	2.69	-0.20

* Power factor corrected with 2-kvar Westinghouse Dyna-Vac capacitors.

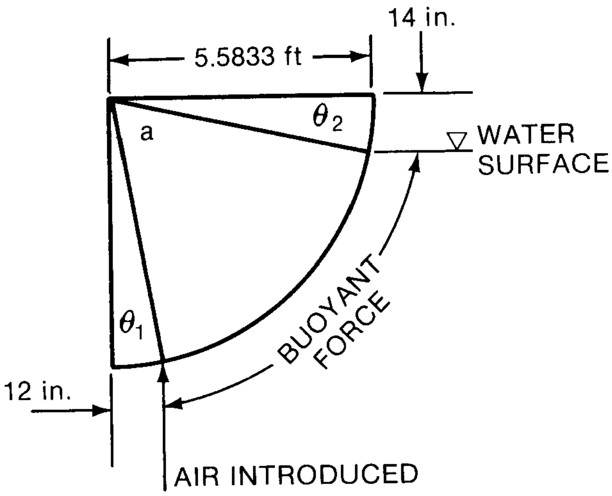
† Drives 12 and 13 are 5-hp units; all other motors are 7.5-hp units; all motors are 480 V, 60 Hz, 3 phase, 1140 rpm, TEFC, S.F. = 1.15; shafts 11 and 12 are equipped with standard density media; shafts 13 to 15 are equipped with high density media.

TABLE 4-4. RESULTS OF RBC MECHANICAL DRIVE POWER MEASUREMENTS AT THE UPPER MILL CREEK WASTEWATER TREATMENT PLANT, BUTLER COUNTY, OHIO

		Field Measurements at Motor Disconnect					Measurements at Motor Starter with Power Factor Correction*					
Drive No.†	Rotational Speed (rpm)	EMF (volts)	Current (amps)	Power Factor	Apparent Power (kVA)	Actual Power (kW)	EMF (volts)	Current (amps)	Power Factor‡	Apparent Power (kVA)	Actual Power (kW)	Difference in Apparent Power (kVA)
B1	1.52	478	5.8 - 5.9	0.40 - 0.45	4.84	2.06	480	2.2 - 2.7	0.99L - 1.00	2.04	2.04	2.80
B2	1.50	478	5.8 - 6.0	0.33 - 0.47	4.88	1.95	480	1.9 - 3.2	0.98L - 0.99L	2.12	2.10	2.76
B3	1.52	478	5.8 - 6.9	0.34 - 0.64	5.26	2.58	480	2.0 - 4.6	0.97L - 1.00	2.74	2.70	2.52
B4	1.49	478	6.2 - 7.6	0.55 - 0.66	5.75	3.48	476	5.3 - 6.9	0.99L - 1.00	5.03	5.00	0.72
B5	1.52	476	6.0 - 7.7	0.60 - 0.66	5.65	3.56	480	2.8 - 5.3	0.99 - 0.98L	3.37	3.34	2.28
B6	1.50	472	6.0 - 6.9	0.50 - 0.62	5.27	2.95	480	2.9 - 4.4	0.99L - 1.00	3.03	3.02	2.24
B7	1.50	476	5.8 - 7.7	0.26 - 0.67	5.57	2.59	476	1.8 - 5.2	0.99 - 1.00	2.89	2.88	2.68

* Data on size and manufacturer of power factor correction capacitors not available.
† All motors are 7-1/2 hp, 480 V, 60 Hz, 3 phase, 1165 rpm, TEFC, S.F. = 1.15; shafts B1 to B3 are equipped with standard density media; shafts B4 to B7 are equipped with high density media.
‡ L indicates leading.

into multiple air cups. Normally, 4-in. deep air cups are employed, although 6-in. deep cups are available where increased torque is needed. The radius of air driven RBC media is reduced from 5 ft-11 in. to 5 ft-7 in. so that attachment of the 4-in. air cups results in the same 11 ft-10 in. media diameter as with Autotrol's standard mechanically driven unit. The available angle, a, over which the buoyant force can act with air drive media is calculated below:



$\sin \theta_1 = 1/5.5833 = 0.1791$

$\theta_1 = 10.3^o$

$\sin \theta_2 = 1.1667/5.5833 = 0.2089$

$\theta_2 = 12.06^o$

$a = 90^o - (\theta_1 + \theta_2) = 67.64^o$

The 14-in. wide air trays provide 28 lineal ft around the media periphery (24 rows x 1.1667 ft) to capture rising air bubbles. When multiplied by shaft length, this peripheral footage represents approximately 75 percent of the circumferential area of an 11 ft-10 in. diameter cylinder. Assuming a 2-ft total gap between air trays on the longitudinal axis decreases the total circumferential area available to trap rising air bubbles to roughly 69 percent of the surface area presented by a 25-ft long, 11 ft-10 in. diameter cylinder.

As the orientation of the air cup openings changes during rotation through the angle a, the volume of initially entrapped air bubbles that can be retained within the cups continually decreases. The effective cup volume per 4-in. deep tray at the 10.3^o air introduction angle, θ_1, is 0.653 cu ft (1). The total effective volume of air that can be trapped at a rotational speed of 1 rpm is 180 cu ft (276 trays x 0.653 cu ft/tray). If air was uniformly distributed through the 47 diffusers in the air distribution system for a 25-ft shaft, the minimum total air volume that would need to be supplied to fill the 4-in. air cups at the point of air introduction is 240 cu ft (180 cu ft/0.75), assuming no air is lost between trays within each of the 24 rows. The static wastewater head in the air cup at the point the air is introduced is normally 2.06 psig; therefore, to fill each cup at the point of air introduction requires 240(14.7 + 2.06)/14.7 or 273.6 scfm at 1 atm. barometric pressure and a wastewater temperature of 68^{o}F.

If each cup is immediately filled at the point of air introduction, the total torque around the sector bounded by angle a is 7355 ft/lb and the work that would be performed at a rotational velocity of 1 rpm would be 1.40 hp. Autotrol (2) recommends that centrifugal blowers be designed for at least 3-psig output and positive displacement blowers be designed for a somewhat higher pressure rise because of losses from the inlet and outlet silencers. At 68°F and 3 psig, 273.6 scfm is equivalent to 3.34 adiabatic hp. If the compressor and motor have a combined efficiency of 50 percent for a 3-psig air supply, the overall power efficiency per horsepower of work performed when each cup is filled immediately at the point of air introduction is 21.0 percent [1.40/(3.34/0.50)]. Even if the air flow were cut in half and the system rotated at 1 rpm, the output work of 0.91 hp would only represent an overall power efficiency of 27.2 percent [0.91/(1.67/0.50)] at the same assumed 50-percent combined efficiency for the compressor and motor. These calculations illustrate the well known fact that an air drive system cannot compete in energy efficiency with a mechanical drive system at equal rotational speeds. In actuality, air driven systems are designed to rotate from 1.0 to 1.3 rpm versus the recommended 1.6 rpm for mechanical systems and, hence, an actual energy comparison between air and mechanical systems depends on the overall system designs.

4.3.2 Blower Design

Autotrol's design manual (2) recommends that 250 cfm of blower capacity be provided for each shaft. According to Sullivan (1), these recommendations have been revised and the current recommendation calls for 350 cfm of operating capacity plus additional standby capacity. Maximum normalized air flow at ambient conditions (68°F) with 4-in. air cups for various rotational velocities is presently indicated by the manufacturer (3) to be as follows:

	Air Flow (acfm*) at Indicated Rotational Speed		
Rotational speed (rpm)	1.0	1.2	1.4
Standard density media	100†	150†	220†
High density media	145†	225†	350†

* acfm = actual cfm

† Wastewater temperatures below 68°F or use of 6-in. air cups will increase these values.

The power requirements for air drive plants are more difficult to predict than those for mechanical drive plants because the designer has a more direct impact on power consumption. The sizing and design of the air distribution system will directly affect the line losses and, therefore, the discharge pressure at which the compressor must operate. In designing the distribution system, the designer is faced with the classical trade-off of higher capital costs for the distribution system versus reduced power costs resulting from decreased line losses. The usual industrial practice is to design for headlosses in the range of 0.1 to 0.6 psi/100 ft of line.

Design of centrifugal compressors is a rather precise technology, and most equipment manufacturers can provide units that are relatively efficient at the design conditions. It is extremely important that the design conditions stipulated by the engineer match actual operating conditions as closely as possible. Compressor operation at conditions other than those for which the compressor was designed can result in substantial loss of efficiency.

Figures 4-1 and 4-2 are modified performance curves for a centrifugal compressor extrapolated from typical performance curves normally supplied by a vendor, i.e., the volume versus discharge pressure and the horsepower versus pressure curves. It is apparent in Figure 4-1 that the input horsepower required is a nearly linear function of the inlet air flow. The difference in input power requirements for 2.6- and 3.3-psig discharge pressures is minimal.

Figure 4-2 illustrates why a disproportionately small reduction in input power is achieved at reduced operating pressures. The efficiency of the compressor shown decreases rapidly as the output pressure drops below the design point of 3.3 psig. This characteristic of centrifugal compressors requires that the designer carefully analyze system operation to minimize power consumption and coordinate the design process with the compressor manufacturer.

Consider an example of 200 ft of 16-in. steel pipe designed to carry 3200 scfm (Point A), which would produce friction losses of 0.8 psi or roughly 24 percent of the blower discharge pressure of 3.3 psig. If the compressor inlet is then throttled to back the air flow down to 1600 scfm, the friction losses in the line would drop to 0.14 psi. This action would decrease the compressor discharge pressure 0.66 psi below the design point to approximately 2.6 psig (hypothetical Point B), and the compressor's efficiency would be reduced from 72 percent to about 42 percent. Consequently, the attempt to save power by a 50-percent throttling of the compressor would have resulted in only a 19-hp or 33-percent decrease in power consumption.

For those facilities in which significant variations in air flow requirements are anticipated, consideration should be given to using multiple compressors with different design points, both for air flow and discharge pressure. An additional recommendation is that curves similar to those developed in Figures 4-1 and 4-2 be required submittal data from the manufacturer along with the standard performance curves.

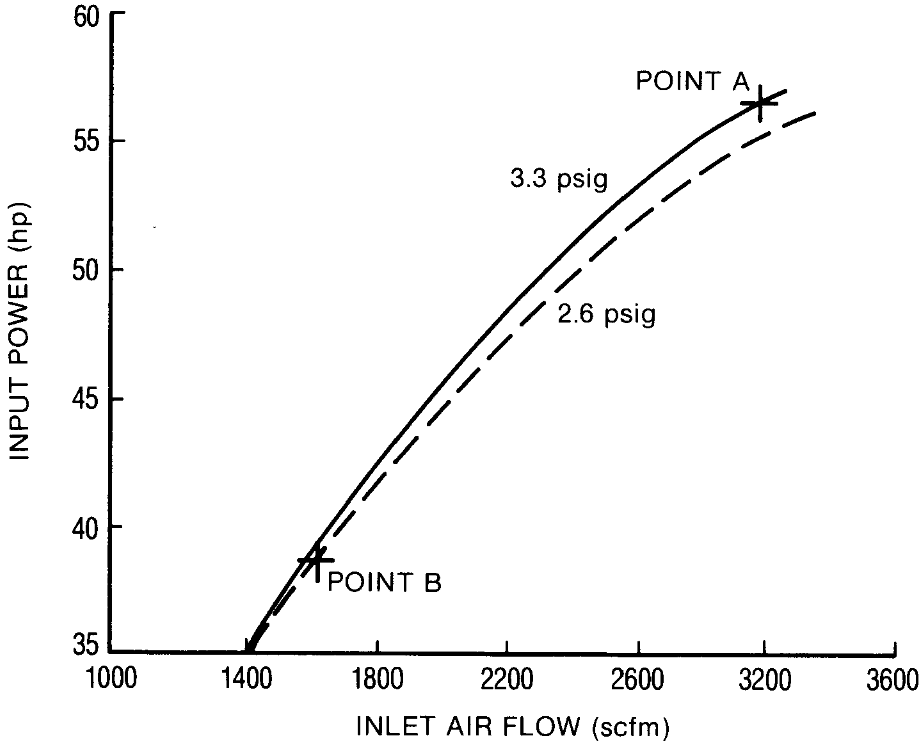


Figure 4-1. Typical centrifugal compressor horsepower versus air flow curve.

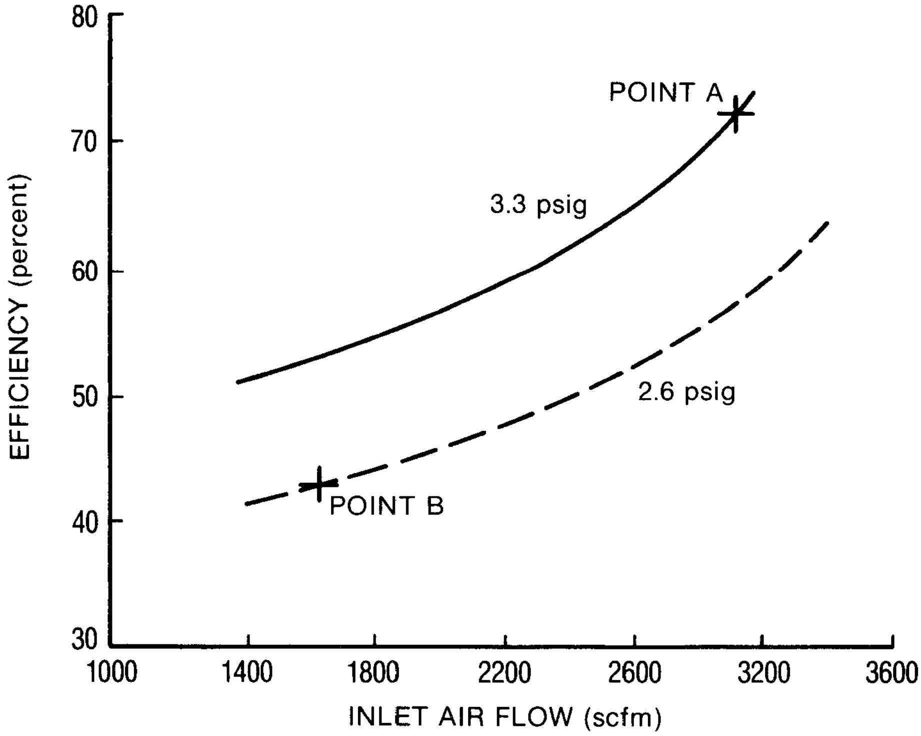


Figure 4-2. Typical centrifugal compressor efficiency versus air flow curve.

4.3.3 Field Measurements of Air Flow Versus Rotational Speed

As previously discussed, the power consumption for an air drive RBC system can only be accurately estimated once the motor and blower characteristics, line losses, and operating range have been addressed. The single-valued curves of air flow versus rotational speed for standard and high density media in the Autotrol design manual (2) were developed from measurements at several pilot- and full-scale installations. These curves fall within the range of values that were summarized in several internal Autotrol documents made available to the writers.

Since information on speed versus air flow relationships is essentially nonexistent to the design community at large, a study was made at two air drive installations (Lower East Fork and Indian Creek) in the Cincinnati area. Flexible hoses and a sharp-edged orifice plate inserted in a specially constructed flanged PVC pipe apparatus were used to tap into air supply headers and measure total air flow to individual RBC shafts. The apparatus was transported intact to and calibrated by the Cox Instrument Company of Detroit, which certified the accuracy of the measuring device to having less than 3 percent error.

The main characteristics of the two plants studied and the results obtained are presented in Table 4-5 and Figures 4-3 and 4-4. The Autotrol design curves for high density media (3) are superimposed on Figure 4-3 for 6-in. deep air cups with assumed heavy biological growth and 4-in. deep cups with assumed normal biological growth for wastewater temperatures of 50 and 53.6^{o}F, respectively. The Autotrol design curves for standard density media (3) are superimposed on Figure 4-4 for heavy growth at a wastewater temperature of 50^{o}F and normal growth at 53.6^{o}F. In general, the manufacturer's recommended design curves underestimate the actual air requirements measured. While data from two plants are not sufficient to describe the rotational responses that may prevail at other RBC air drive installations, they do indicate that the recommended design relationships are not always applicable. Furthermore, the load cell readings for the Lower East Fork plant do not indicate that the biofilm being carried by these units is excessive. The first-stage units at Indian Creek run with the inlet air valves wide open at all times. The rotational responses of the first-stage units at the highest air flow rates measured reflect throttling back of the other stages beyond their normally throttled conditions during the period of air flow measurement. This plant is operating at 40 percent of design flow. These results are discussed further in Section 5.

TABLE 4-5. SELECTED CHARACTERISTICS OF LOWER EAST FORK AND INDIAN CREEK PLANTS

Parameter	Lower East Fork	Indian Creek
Shaft length	25 ft	20 ft
Media density	High	Standard
Air cups	4 in. and 6 in.	4 in.
No. of Trains	3	2
Shafts per train	9	3
Shaft numbers measured	1,3,5,9	1,2,3

Curve Designation in Figures 4-3 and 4-4	Air Cup Depth (in.)	Stage	Date Measured (1982)	Biofilm Thickness (in.)	
				Measured*	Observed**
A	6	1	2/11	0.050	-
B	6	1	3/15	0.044	-
C	6	1	3/17	0.042	-
D	4	3	3/15,3/17	0.038,0.037	-
E	4	5	2/23	0.045	-
F	4	9	2/23	-	A/B
G	4	1	3/2	-	C
H	4	2	3/11	-	B
I	4	3	3/2	-	A
J	4	1	3/11	-	C

* From manufacturer's load cell calibration curve.
** A = light growth; B = normal growth; C = heavy growth.

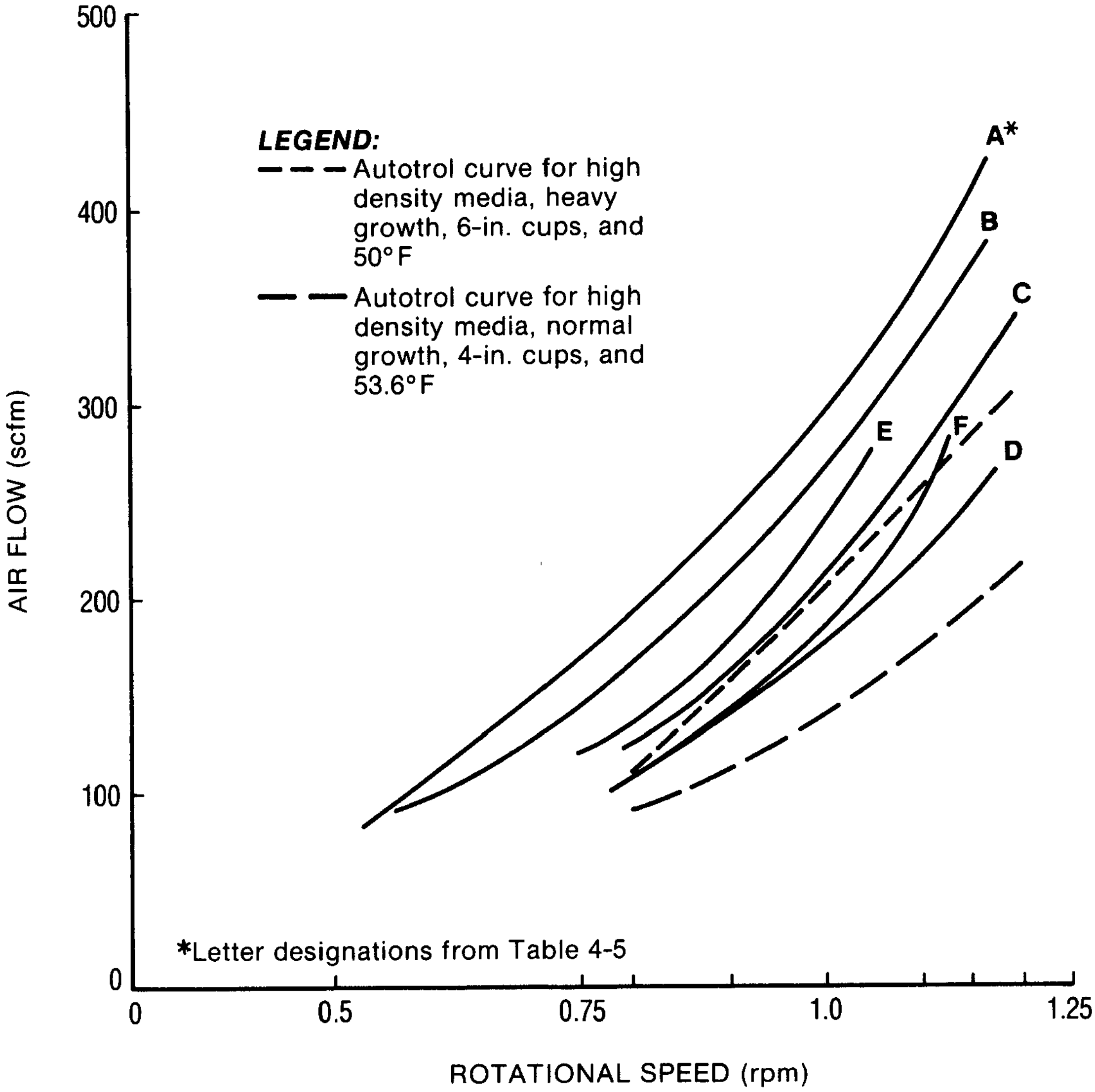


Figure 4-3. Summary of air flow versus rotational speed measurements made at Lower East Fork-Little Miami River Regional Wastewater Treatment Facility, Clermont County, Ohio.

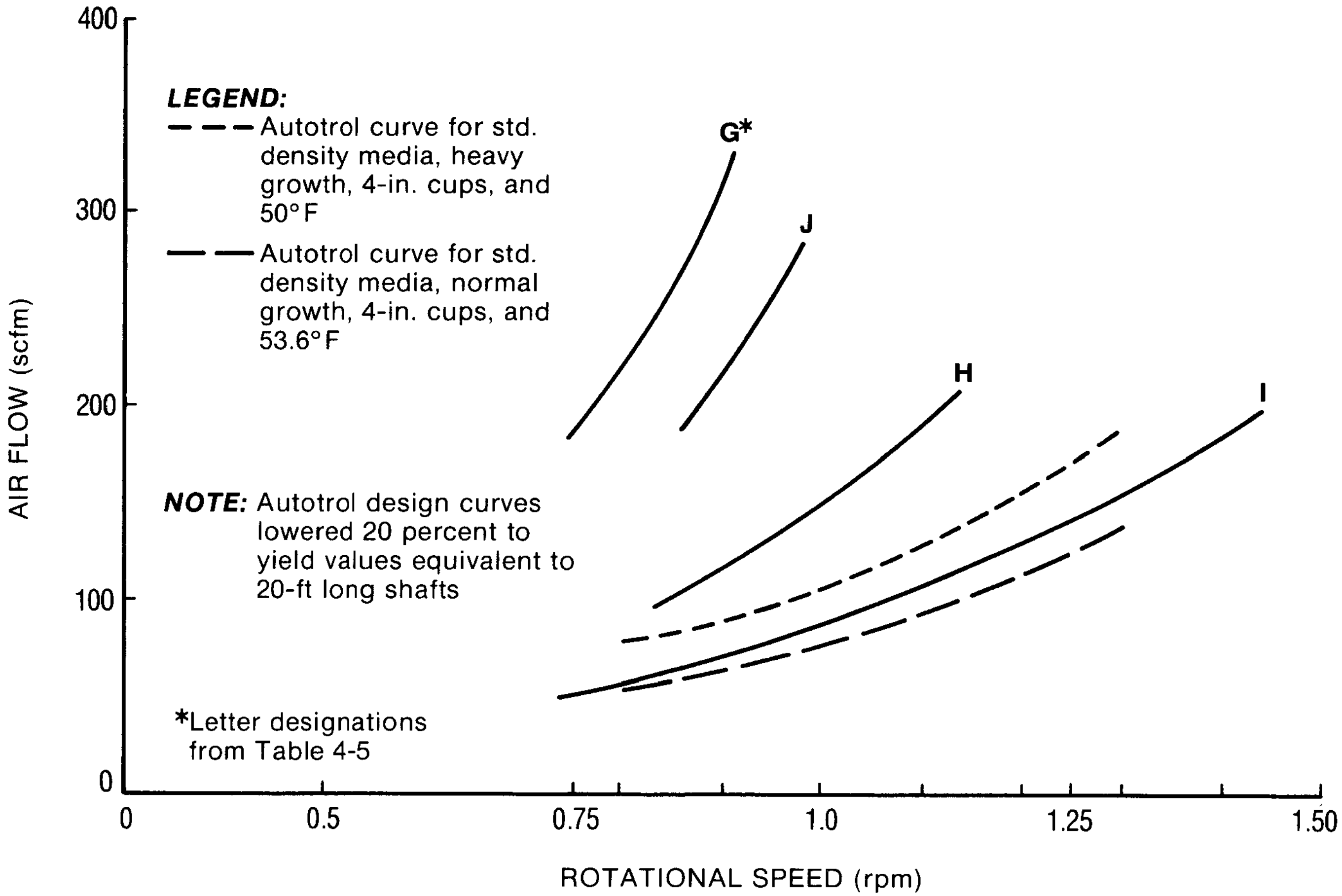


Figure 4-4. Summary of air flow versus rotational speed measurements made at Indian Creek Wastewater Treatment Plant, Hamilton County, Ohio.

4.4 Mechanical Drive Systems

4.4.1 Clean Media Power Measurements

Clean media power measurement data for mechanically driven RBC units manufactured by Clow and Autotrol Corporations have been reviewed and summarized by Chesner and Iannone (4). The results of these clean media tests indicated the following:

1. The power required to rotate the media increased as a cubic function of the rotational velocity.

2. Power losses from the motor, drive, and gear box were small in relation to the power required to overcome the drag imposed by the media.

3. The ratio of power consumed to media surface area at a given rotational velocity was reasonably constant for both the Clow and Autotrol units. The particular ratio observed varied with the manufacturer.

4. Power consumption for units with rotational velocities of 1.4 to 1.7 rpm varied from 1.56 to 2.04 hp (1.16 to 1.52 kW) for shafts with 100,000 sq ft of media surface area and from 1.98 to 2.60 hp (1.48 to 1.94 kW) for shafts with 150,000 sq ft of media surface area.

According to Sullivan (1), the power requirements for field applications is not a perfect cubic function of the rotational velocity for all mechanical drive RBC systems. Other energy-consuming factors exist, independent of speed, that can lead to a less-than-cubic relationship between power and speed. Accordingly, the cubic relationship should not be used indiscriminately.

4.4.2 Field Power Measurements

Field measurements of the power requirements for mechanical drive RBC systems were made by Environmental Resources Management, Inc. (ERM) for EPA's Office of Water Program Operations using an electric power/demand analyzer (5), by the Roy F. Weston Company for EPA's Municipal Environmental Research Laboratory using polyphase wattmeters (4), and by EPA staff personnel using an industrial power analyzer (6). The Roy F. Weston data were challenged by the manufacturers. Since these data could not be subsequently verified, they are not considered in this document. Selected results of the ERM and EPA staff studies, however, are summarized in Table 4-6.

TABLE 4-6. POWER MEASUREMENTS FOR MECHANICAL DRIVE RBC PLANTS

Plant Site/ WW Temp.	Stage Measured	Motor Size (hp)	Biofilm Growth	Surface Area (sq ft)	Observed Speed (rpm)	Recorded Power (kW)	Recorded Power (hp)	Recorded Power Factor	Manufacturer/ Reference
Cheyney, Pa./	1	5	M	128,250	1.5	1.21	1.62	0.26	Lyco/5
t°F	2	5	L	165,750	1.5	1.22	1.64	0.26	
Pennsville,	1	7.5	H	120,000	1.5	2.60	3.49	0.59	Lyco/5
N.J./68°F	1	7.5	H	120,000	1.5	2.48	3.33	0.59	
	2	5	M	150,000	1.5	2.32	3.11	0.57	
	2	5	M	150,000	1.5	2.00	2.69	0.54	
	3	5	M	180,000	1.5	1.78	2.39	0.50	
	3	5	M	180,000	1.5	1.64	2.20	0.48	
King of Prussia,	1	5	L	100,000	1.5	1.64	2.20	0.36	Walker
Pa. (Matsunk	2	5	L	100,000	1.5	1.64	2.20	0.36	Process/5
Plant)/61°F	3	5	L	150,000	1.5	2.39	3.21	0.52	
	3	5	L	150,000	1.5	2.31	3.10	0.48	
	5	5	L	150,000	1.5	2.27	3.04	0.46	
Philadelphia,	1	5	M	100,000	1.5	2.33	3.12	0.62	Clow/5
Pa. (Northeast	1	5	M	100,000	1.5	2.53	3.39	0.65	
Plant)/54°F	1	5	M	100,000	1.5	2.05	2.75	0.58	
	1	5	M	100,000	1.5	2.83	3.80	0.71	
	1	5	M	100,000	1.5	2.41	3.23	0.66	
	1	5	M	100,000	1.5	2.12	2.84	0.61	
	1	5	M	100,000	1.5	2.33	3.12	0.61	
Marshall,	1	5	M	100,000	1.5	2.48	3.33	0.48	Walker
Wisc./52°F	2	5	M	100,000	1.5	2.04	2.73	0.43	Process/5
	3	5	L	150,000	1.5	2.15	2.88	0.43	

(continued)

TABLE 4-6. (continued)

Plant Site/ WW Temp.	Stage Measured	Motor Size (hp)	Biofilm Growth	Surface Area (sq ft)	Observed Speed (rpm)	Recorded Power (kW)	Recorded Power (hp)	Recorded Power Factor	Manufacturer/ Reference
Canonsburg, Pa.	1	7.5	M	100,000	1.5	1.68	2.25	0.28	Autotrol/5
(Canonsburg-	1	7.5	M	100,000	1.5	2.00	2.68	0.31	
Houston	2	7.5	M	100,000	1.5	2.32	3.11	0.38	
Plant)/61°F	3	7.5	L	100,000	1.5	1.45	1.94	0.26	
	3	7.5	L	100,000	1.5	1.57	2.11	0.27	
	3	7.5	M	100,000	1.5	1.77	2.37	0.29	
	4	7.5	L	100,000	1.5	1.36	1.82	0.24	
	5	7.5	L	150,000	1.5	1.71	2.29	0.30	
	5	7.5	L	150,000	1.5	1.92	2.57	0.35	
St. Clairsville,	1	5	M	100,000	1.5	1.85	2.48	0.37	Clow/5
Ohio/62°F	1	5	M	100,000	1.5	3.13	4.20	0.54	
	2	5	M	100,000	1.5	2.10	2.82	0.42	
	3	5	L	150,000	1.5	2.67	3.58	0.50	
	3	5	L	150,000	1.5	1.95	2.61	0.40	
	4	5	L	150,000	1.5	2.21	2.96	0.45	
	5	5	L	150,000	1.5	2.13	2.86	0.42	
Fairmont, W.Va./	1	5	M	100,000	1.5	1.80	2.41	0.53	Clow/5
62°F	1	5	M	100,000	1.5	1.77	2.37	0.53	
	2	5	M	100,000	1.5	1.62	2.17	0.51	
	3	5	M	100,000	1.5	1.48	1.98	0.51	
	4	5	M	100,000	1.5	1.45	1.94	0.50	
	4	5	†	100,000	1.5	1.60	2.15	0.52	
	5	5	L	100,000	1.5	1.45	1.94	0.49	
	5	5	†	100,000	1.5	1.63	2.19	0.53	

(continued)

TABLE 4-6. (continued)

Plant Site/ WW Temp.	Stage Measured	Motor Size (hp)	Biofilm Growth	Surface Area (sq ft)	Observed Speed (rpm)	Recorded Power (kW)	Recorded Power (hp)	Recorded Power Factor	Manufacturer/ Reference
Mount Pleasant, Mich./58°F	1	5	H	120,000	1.5	2.06	2.76	0.58	Walker Process/5
	2	5	H	120,000	1.5	1.81	2.43	0.55	
	3	5	M	120,000	1.5	1.81	2.43	0.54	
	4	5	M	170,000	1.5	3.08	4.13	0.68	
	5	5	M	170,000	1.5	2.76	3.70	0.67	
	6	5	L	170,000	1.5	2.81	3.77	0.66	
Holt, Mich. (Delhi Charter Twp. Plant)/58°F	1	7.5	H	100,000	1.7	2.28	3.06	0.35	Autotrol/5
	1	7.5	H	100,000	1.7	2.33	3.12	0.35	
	1	7.5	H	100,000	1.7	2.99	4.01	0.45	
	2	7.5	H	100,000	1.7	2.16	2.90	0.35	
Birdsboro, Pa./ 60°F	1	7.5	L	100,000	1.5	1.95	2.61	0.21	Autotrol/5
	1	7.5	L	100,000	1.5	1.62	2.17	0.18	
	2→4	7.5	L	138,000	1.5	1.56	2.09	0.16	
	2→4	7.5	L	138,000	1.5	1.85	2.48	0.22	
	2→4	7.5	L	138,000	1.5	1.83	2.45	0.19	
Johnson Creek, Wisc./47°F	1→4	7.5	M	125,000	1.5	2.39	3.21	0.82	Clow/5
	1→4	7.5	M	125,000	1.5	2.38	3.19	0.82	
Lake Mills, Wisc./55°F	1	5	M	100,000	1.5	2.19	2.94	0.46	Walker Process/5
	2	5	M	100,000	1.5	2.16	2.90	0.43	
	2	5	†	150,000	1.5	3.02	4.05	0.53	
	3	5	L	150,000	1.5	2.40	3.22	0.46	
	4	5	L	150,000	1.5	2.29	3.07	0.43	
	5	5	L	150,000	1.5	2.09	2.80	0.41	

(continued)

TABLE 4-6. (continued)

Plant Site/ WW Temp.	Stage Measured	Motor Size (hp)	Biofilm Growth	Surface Area (sq ft)	Observed Speed (rpm)	Recorded Power (kW)	Recorded Power (hp)	Recorded Power Factor	Manufacturer/ Reference
East Washington, Pa. (WEWJA Plant)/57°F	1	7.5	M	100,000	1.8	1.80	2.41	0.25	Autotrol/5
	1	7.5	M	100,000	1.8	2.27	3.04	0.32	
	1	7.5	M	100,000	1.8	2.23	2.99	0.34	
	2	7.5	M	100,000	1.8	2.78	3.72	0.43	
	3	7.5	M	100,000	1.8	2.09	2.80	0.32	
	4	7.5	L	150,000	1.8	2.80	3.75	0.40	
	5	7.5	L	150,000	1.8	2.19	2.94	0.30	
	6	7.5	L	150,000	1.8	2.71	3.63	0.38	
	6	7.5	L	150,000	1.8	2.61	3.50	0.41	
	6	7.5	L	150,000	1.8	2.50	3.35	0.36	
LeSourdsville, Ohio/†°F	1	7.5	†	100,000	1.66	2.55	3.42	0.21	Autotrol/6
	2	7.5	†	100,000	1.66	2.11	2.83	0.34	
	3	7.5	†	150,000	1.54	3.69	4.95	0.38	
	4	7.5	†	150,000	1.46	3.80	5.10	0.44	
	5	7.5	†	150,000	1.50	3.63	4.87	0.37	
Cincinnati, Ohio (Upper Mill Creek Plant)/†°F	1	7.5	C/B	100,000	1.5	2.9	3.89	0.42	Clow/6
	2	7.5	C/B	100,000	1.5	2.7	3.62	0.40	
	3	7.5	B	100,000	1.5	2.9	3.89	0.49	
	4	7.5	B	150,000	1.5	3.1	4.16	0.60	
	5	7.5	B	150,000	1.5	2.6	3.49	0.63	
	6	7.5	A	150,000	1.5	2.7	3.62	0.56	
	7	7.5	A	150,000	1.5	2.2	2.95	0.46	

*L = growth < 0.031 in.; M = growth of 0.031-0.063 in.; H = growth of 0.064-0.125 in.; A = visually light growth; B = visually normal growth; C = visually heavy growth.

→ indicates multiple stages per shaft.

† indicates not observed or recorded.

Four of the five current RBC manufacturers are represented in Table 4-6. Shaft lengths of all units reported in this table were confined to a range of 23 to 27 ft, while media diameters varied from 11 to 12 ft. Rotational speeds for most units were measured at 1.5 rpm; several units, however, were clocked as high as 1.8 rpm.

According to Chesner and Iannone (4), manufacturers' estimates of power requirements for mechanical drive RBC's range from 2.7 to 3.4 hp/shaft (2.0 to 2.5 kW/shaft) for standard density media. The manufacturers' estimated range for high density media is 3.5 to 4.2 hp/shaft (2.6 to 3.1 kW/shaft).

The 80 drive units field tested by ERM that were selected for inclusion in Table 4-6 by the authors plus the 12 units evaluated by EPA had a mean power requirement of 2.98 hp/shaft (2.22 kW/shaft) with a standard deviation of 0.71 hp/shaft (0.53 kW/shaft). The highest recorded power usage was 5.10 hp/shaft (3.80 kW/ shaft) at LeSourdesville, Ohio, and the lowest was 1.62 hp/shaft (1.21 kW/ shaft) at Cheyney, Pennsylvania.

Of the above 92 shaft and drive assemblies, a total of 55 were equipped with media having a surface area of 100,000 to 128,250 sq ft. Media having a surface area in this range are generally regarded in the industry as representing standard density media. The media surface area of the other 37 units varied from 138,000 to 180,000 sq ft, a range characteristic of high density media. The average measured power consumption for the standard density units was 2.80 hp/shaft (2.09 kW/shaft) with a standard deviation of 0.62 hp/shaft (0.46 kW/shaft). For the high density units, the average power requirement recorded was 3.22 hp/shaft (2.40 kW/shaft) with a standard deviation of 0.79 hp/shaft (0.59 kW/shaft). The above values agree well with the manufacturers' estimates of mechanical drive power requirements for standard density media and are slightly lower than the manufacturers' estimates for high density media.

When field-measured power levels exceed the means indicated above for standard and high density media by one to two standard deviations or more, the operator should investigate whether the higher power consumption is being caused by equipment problems, heavier-than-normal biofilm growth, or both. Potential equipment problem areas include improper alignment, inadequate lubrication, excessive rotational speed, excessive belt tension or belt slippage, and general wear and deterioration of the drive components.

4.5 References

1. Personal communication from R. A. Sullivan, Autotrol Corporation, Milwaukee, Wisconsin, to J. A. Heidman, USEPA, Cincinnati, Ohio, April 14, 1982.

2. Autotrol Wastewater Treatment Systems Design Manual. Autotrol Corporation, Bio-Systems Division, Milwaukee, Wisconsin, 1978.

3. Aero-Surf Energy Requirements. Autotrol Corporation internal report, Milwaukee, Wisconsin, April 1, 1981.

4. Chesner, W. H. and J. Iannone. Review of Current RBC Performance and Design Procedures. Report prepared for USEPA, Municipal Environmental Research Laboratory, Cincinnati, Ohio, under Contract No. 68-02-2775 by Roy F. Weston, Inc., (Publication pending).

5. Environmental Resources Management, Inc. Evaluation of the Energy Requirements for Rotating Biological Contactors (RBCs). Report prepared for USEPA, Office of Water Program Operations, Washington, D.C., under Contract No. 68-01-6622, (Publication pending).

6. Heidman, J. A., W. W. Schuk, and A. C. Petrasek. Field Measurements of Power Consumption and Air Flow at RBC Installations. Internal report, USEPA, Municipal Environmental Research Laboratory, Test and Evaluation Facility, Cincinnati, Ohio, May 5, 1982.

SECTION 5

DESIGN CONSIDERATIONS

5.1 Introduction

RBC systems can be employed for organic removal, nitrification, organic removal plus nitrification, and/or denitrification. Several design approaches are available to achieve the above objectives, including the use of pilot plant studies, mathematical models, and empirial procedures, all of which are discussed in subsequent sections. Pilot studies should be conducted where economic considerations and feasibility warrant such efforts or where atypical municipal wastewater characteristics are anticipated. If desired, calibration of some of the more complex mathematical models can be combined with an RBC pilot program to obtain estimates of model coefficients. Where pre-design pilot plant evaluations are not or cannot be undertaken, the designer must use empirical design approaches, exercising technical judgement regarding their applicability and adaptibility to site-specific conditions.

5.2 Mathematical Models

The previous discussion in Section 2.7.1 has shown that not all the biofilm on an RBC necessarily contributes to observed organic removals. Hence, the mathematical models that attempt to duplicate all the factors contributing to substrate removal in a fixed film system must combine equations for mass transfer for both electron donor and acceptor with equations for microbial metabolism. In RBC systems, mass transfer resistances associated with both the wastewater film and the biofilm result in significant concentration gradients from the bulk liquid to biological reaction sites. Consequently, the overall rates of reaction may be controlled by metabolism or by diffusion.

Mathematical models that take a completely deterministic approach by attempting to incorporate all of the factors affecting RBC performance provide considerable insight into those variables and ranges of variables that impact the RBC process. Employing this approach in design, however, entails making certain assumptions about the wastewater film thickness in the atmospheric portion of the cycle, mixing of this wastewater film with the bulk liquid, the effect of RBC surface shape on mixing and surface biofilm depth and uniformity, biofilm density, diffusion coefficient(s) within the biofilm and possible variation with depth and/or the type of organisms that predominate, and biochemical kinetic parameters. A mathematical model approach has been applied in some design situations in conjunction with pilot plant studies carried out on the wastewater in question. Calibration of the model coefficients can be incorporated in the pilot plant program and is a necessary step in the use of complex mathematical models for design purposes.

5.3 Pilot Plant Studies

The best source of RBC design information is a comprehensive on-site pilot plant evaluation. The use of full-scale diameter media are recommended to avoid scale-up problems. As previously indicated, tip speed is not a suitable scale-up parameter. In developing an RBC pilot study, consider the following points:

1. The influent wastewater should be thoroughly characterized. The parameters of interest vary with the degree of treatment required. For example, influent TKN, ammonia nitrogen, pH, and alkalinity are all important parameters when nitrification is required, but are of lesser importance (assuming the values are in the normal range for municipal wastewaters) for a design requiring carbonaceous removal only. Measurement of influent suspended and volatile suspended solids, total BOD_5, soluble BOD_5, and sulfide are of importance in any characterization. Both the hydraulic and organic diurnal patterns should also be examined.

2. Either raw wastewater screening or primary clarification should be utilized ahead of the RBC pilot unit depending on the anticipated choice for the final design. Where no final decision has been made, the effectiveness of both options on RBC performance should be addressed.

3. The upper loading limit for any stage should be 2.5 to 3 lb soluble BOD_5/day/1000 sq ft.

4. The change in total COD across a stage (unsettled samples) directly measures oxygen transfer, provided that no nitrification, denitrification, sulfide oxidation, sulfate reduction, or change in bulk liquor DO levels is occurring.

5. Measurements of changes in soluble components across a stage provide no information on settling characteristics of the suspended solids leaving the RBC reactor. Settling tests conducted in 1-liter cylinders provide relative settling information for comparative purposes, but will not duplicate results obtained in full-scale clarifiers. Settling tests carried out in large columns (6 to 8 in. in diameter and 6 to 8 ft deep) are always preferable to 1-liter cyclinder tests. Where column tests are used to determine final clarifier loadings, it is essential that the anticipated effectiveness of the clarifier, i.e., the degree of departure of actual clarifier hydraulics from idealized conditions, be considered (1).

6. Nitrification is slow to develop in cold temperatures, and 8 to 10 wk may be required before a nitrification system approaches equilibrium

conditions. Seeding with a nitrifying sludge, if available, or temperature enhancement should be considered. Either option may be feasible at pilot scale. Where seasonal standards for nitrification are required for the final design, the transition time and temperatures to develop an adequate nitrifying population must be considered.

7. Where more than one RBC stage is included in a pilot plant investigation, interstage data should normally be collected on the parameters of interest. In addition to the parameters cited in item 1, interstage data on DO levels will often prove informative.

8. In any lightly loaded stage, partial nitrification may occur and provide a source of nitrifying organisms and residual ammonia nitrogen for subsequent oxidation in a BOD_5 analysis. Inhibited BOD_5 analyses should be routinely conducted if BOD_5 measurements are meant to measure carbonaceous oxygen demand only.

9. Unless flow equalization is provided, a treatment plant will operate with diurnal flow variations. Dry and wet weather peak load conditions should be considered in the pilot study. Normally, dry weather peak loads are of major concern only where the daily peak-to-average flow ratio exceeds 2.5.

10. Where wastewater temperatures less than 50^{o}F are expected, a pilot study should include operation at these low temperatures if at all possible. Present empirical approaches predict large variations in needed media surface areas at low temperatures (refer to Figures 2-8 and 2-10).

11. Incoming sulfide exerts an additional oxygen demand. Where sulfide is known to be present in the influent wastewater, prechlorination or preaeration may represent potentially cost effective means of eliminating the oxygen demand posed by incoming sulfide.

12. Where process sidestreams (especially heat treatment liquor) are expected to be recycled back through the RBC reactor, the additional loadings from these materials should be incorporated in the pilot study experimental program. Where nitrification is required, potential additional ammonia nitrogen loadings from anaerobic digestion should be considered.

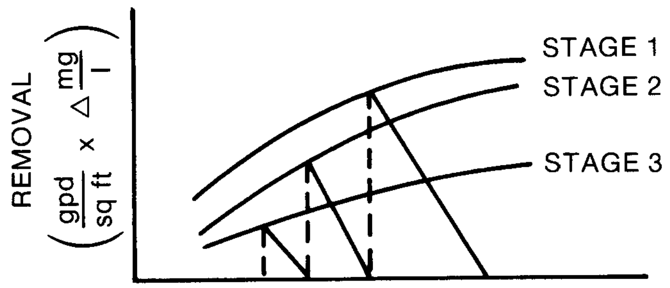
13. In conducting soluble BOD and/or COD analyses, care should be taken to employ uniform procedures for sample filtration and storage. Wastewater samples filtered immediately are apt to have higher soluble organic concentrations than samples filtered after several hours of storage; the converse is true for sludge samples.

14. Solids production data as a function of total and soluble BOD_5 removal and/or total and soluble COD removal should be collected. Sludge thickening characteristics may also require investigation depending on the options under consideration for sludge processing. Leaf tests, press tests, and other analyses related to sludge dewatering may also be appropriate.

15. pH and alkalinity adjustment should be considered whenever nitrification is required and may be cost effective if nitrification reaction rates are limited by pH.

16. A range of system loadings should always be evaluated. In this regard, the number of stages or the relative loading to each stage (unequal stage sizes) should be addressed.

Municipal wastewater is a mixture of hundreds of individual compounds of varying molecular size. The simpler, more readily degradable compounds will be removed in the first stage(s) of any staged system and the more difficult to degrade compounds will tend to predominate in the later stages. For this reason, it is informative to examine pilot plant data separately for each stage. One useful form for performing this analysis is illustrated below (2):



If the removals across each stage, gpd/sq ft x Δmg/l, are plotted as a function of soluble carbon (BOD or COD) in the stage, any line drawn from the X-axis up to a stage curve has a slope of ΔY/ΔX or gpd/sq ft x Δmg/l/Δmg/l or just gpd/sq ft. The slope of such a line, therefore, represents the wastewater flow necessary to achieve a desired soluble carbon concentration in the effluent from any given stage. Although a separate curve is shown for each stage in this example, it is entirely possible that the removal curves for different stages will coincide or overlap. Soluble organic removals then become a function of stage loading only and are independent of the number of stages. The use of the above approach requires that soluble measurements be correlated with settleability data so that the impact of final clarification can be considered.

5.4 Organic Removal Design

5.4.1 Comparison of Available Empirical Design Approaches

When it is not possible and/or feasible to undertake comprehensive RBC pilot plant programs, empirical design curves and procedures developed by the manufacturers of RBC equipment and information developed by others that is available in the technical literature must be relied on as the basis for design. In these situations, detailed characterization of the raw wastewater (and primary effluent if available) should still be carried out if at all possible.

The depth of information provided on various aspects of RBC organic removal design differs considerably among the various manufacturers (3). Loading and performance predictions vary depending on the particular set of design conditions that are applicable. For example, according to the Autotrol (4) and Clow (5) manuals, the design loading is the same in the presence or absence of a primary clarifier, but Manufacturer X (6) applied a correction factor of 1.2 to the computed media surface area when a primary clarifier was to be omitted. Lyco (7) utilizes applied total BOD_5 as the controlling design parameter, whereas Autotrol and Clow use applied soluble BOD_5. Manufacturer X also used applied soluble BOD_5. Differences in other items such as recommended wastewater temperature correction factors were presented previously in Section 2.

To provide perspective on the range of predicted performance that results from using various manufacturers' design methods, predicted effluent quality was examined for a range of loadings for the case where both influent and effluent soluble-to-total BOD_5 ratios were assumed to be 0.5. The results of this exercise are presented in Figure 5-1. The three Lyco predictions are based on total influent BOD_5 concentrations of 100, 150, and 225 mg/l. The numbers in parentheses for Manufacturer X represent the influent soluble BOD_5 concentration used to determine the indicated data point. Both Autotrol and Clow predict identical relationships for the loading ranges examined. Published definitive design procedures for Crane-Cochrane and Walker Process were not available when this document was prepared (September 1982).

It is also informative to reexamine the various manufacturers predictions when the results are plotted as mass of BOD_5 removed per mass of BOD_5 applied as shown in Figure 5-2. These organic loadings were also based on a soluble-to-total BOD_5 ratio of 0.50 for Autotrol, Clow, and Manufacturer X. For a given mass of BOD_5 applied, each manufacturer predicts that mass removal increases with increasing wastewater concentration, although individual predictions vary. The same general relationship between mass of BOD_5 applied and removed has been observed to hold in various studies reported in the literature (8)(9)(10)(11).

Assumed raw wastewater and primary effluent characteristics for four example organic removal design problems and comparative required media surface areas calcualted using the manufacturers design curves are summarized in Table 5.1. Again, it can be seen that the results vary with the largest difference (Lyco, Example No. 4) reflecting a more conservative temperature correction factor for 45°F.

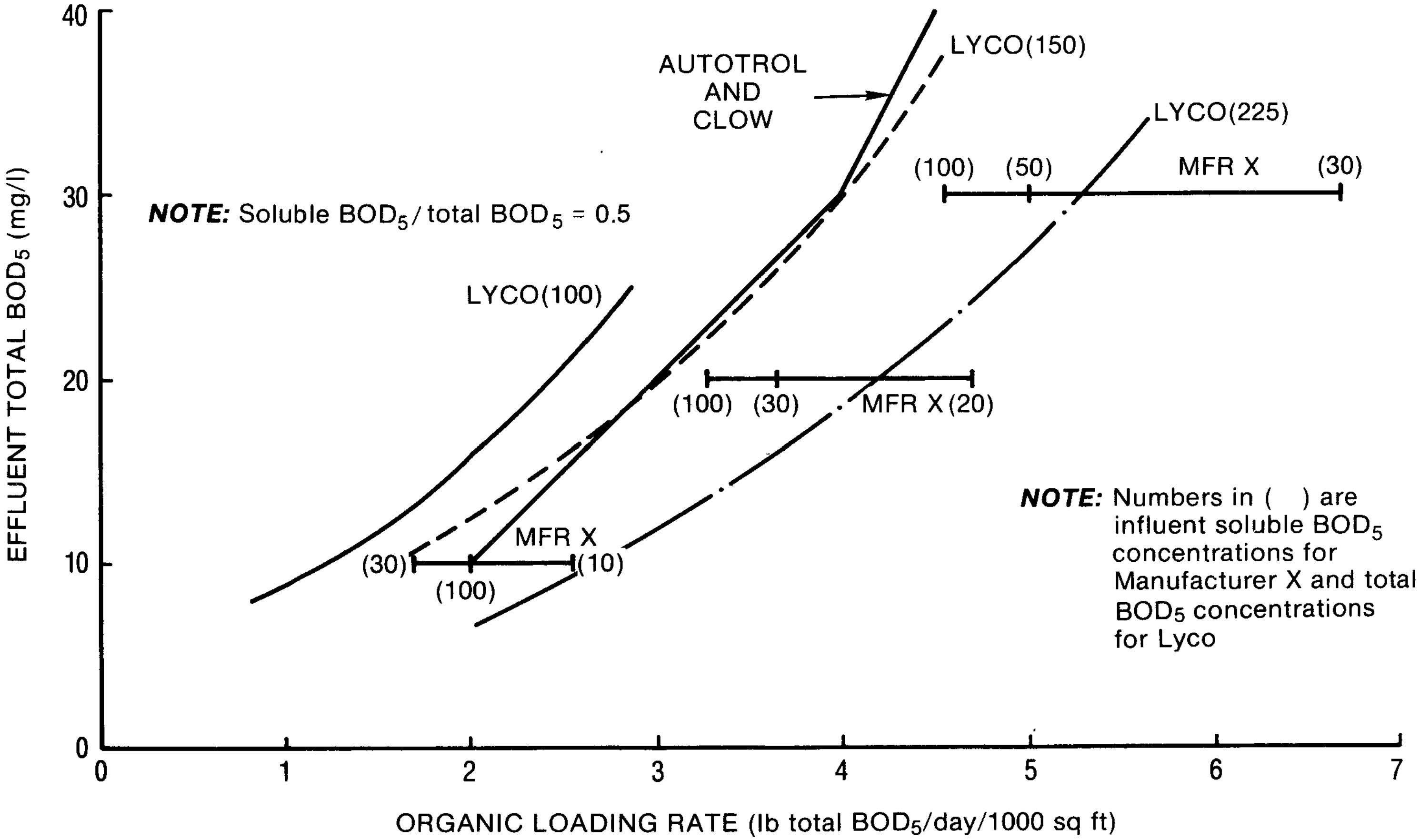


Figure 5-1. Effluent BOD_5 as a function of organic loading for selected RBC manufacturers design techniques.

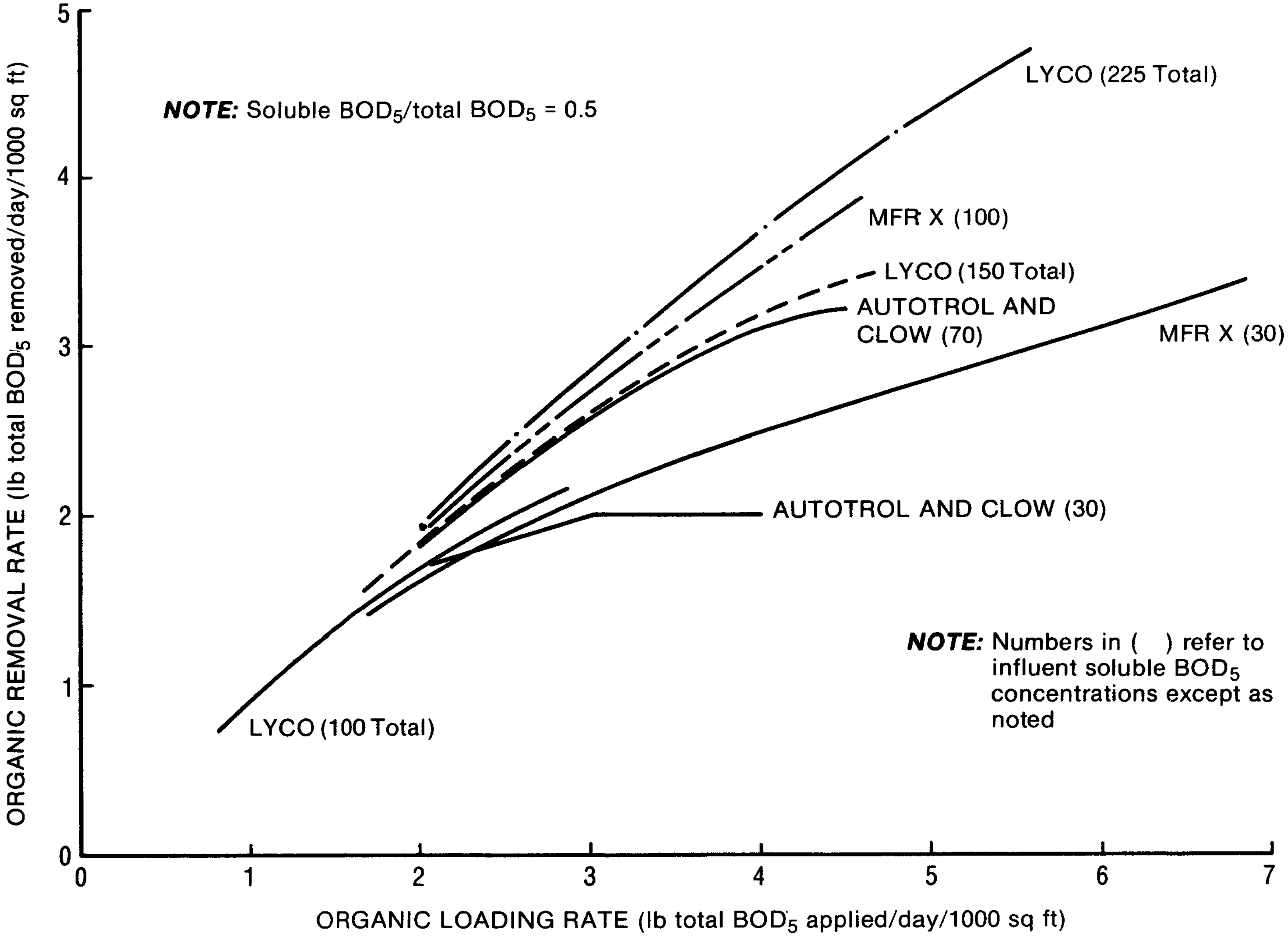


Figure 5-2. Organic removal as a function of organic loading for selected RBC manufacturers design techniques.

TABLE 5-1. WASTEWATER PARAMETERS AND REQUIRED MEDIA SURFACE AREAS FOR EXAMPLE RBC ORGANIC REMOVAL DESIGN PROBLEMS

Parameter	Design Example No. 1	2	3	4
Average flow (mgd)	1.0	1.0	1.0	1.0
Raw wastewater $TBOD_5$ (mg/l)	125	125	70	125
Raw wastewater $SBOD_5$ (mg/l)	50	50	28	50
Wastewater temperature (^{o}F)	55	55	55	45
Required $TBOD_5$ removal (%)	85	85	85	85
Effluent $TBOD_5$ (mg/l)	18.8	18.8	10.5	18.8
Effluent $SBOD_5$ (mg/l)*	9.4	9.4	5.3	9.4
Primary clarifier $TBOD_5$ removal (%)	30	None	None	30

Design Example No.	Required Media Surface Area (sq ft x 1000) Autotrol(4)	Clow(5)	Mfr X(6)	Lyco(7)
1	286	289	276	327
2	286	289	331	400
3	227	226	310	476
4	375	384	373	654

*Based on an assumed $SBOD_5$:$TBOD_5$ ratio of 0.5 in the final effluent.

This discussion of manufacturers' design procedures serves to illustrate that a range of required media surface areas can easily be computed for various organic removal design situations and that care and judgement must be exercised by the designer in determining appropriate media requirements.

Since predictions of effluent quality depend on empirical correlation of observed results with the various design parameters it is hardly surprising to find variations in predicted performance when using generalized design curves and guidelines. In the absence of pilot plant data for the design in question, any manufacturer's guidelines should be used with discretion. Differences in predicted performance for various mechanically driven RBC systems should be viewed in the context of what assumptions were selected in predicting final effluent quality, as well as any differences that may, in fact, represent true differences in performance capabilities between the various units being marketed.

5.4.2 Comparison of Selected Studies with Empirical Design Approaches

Autotrol has been a leader among manufacturers in publishing alternative RBC design procedures, and its organic removal design curves (4) for mechanically driven units are presented in Figure 5-3. These curves serve as a useful backdrop against which several field studies conducted with Autotrol units can be compared.

Murphy and Wilson (12) treated raw degritted wastewater at the Burlington (Ontario) Skyway Water Pollution Control Plant with a four-stage, 6.6-ft diameter RBC unit. The wastewater had an influent BOD_5 of 120 mg/l and influent suspended solids of 230 mg/l. Hydraulic loading to the RBC unit was varied, but flow to the 4-ft diameter pilot clarifier was kept constant at 350 gpd/sq ft. Effluent soluble BOD_5 concentrations were consistently less than or equal to 10 mg/l at total BOD_5 loadings up to 2 lb/day/1000 sq ft. Effluent suspended solids, however, were usually in excess of 30 mg/l (range of 20 to 70 mg/l) even at these low loadings. It was also observed that 30-min settling tests of RBC effluent in an Imhoff cone consistently underestimated the solids removals attained in the pilot clarifier. In this case, assuming total effluent BOD_5 values twice the soluble concentrations would be in error. Data comparing a 1.6-ft diameter pilot unit with the above 6.6-ft diameter unit demonstrated consistently better overall suspended solids removal when a primary clarifier was used, suggesting that primary clarification for this wastewater would produce better effluent quality. On the other hand, plants at Georgetown, Kentucky (13), and Rhinelander, Wisconsin (14), treat raw (screened only) wastewater and produce effluents as follows:

Plant	Hydraulic Loading (gpd/sq ft)	Total BOD_5 (mg/l)		Suspended Solids (mg/l)	
		Inf.	Eff.	Inf.	Eff.
Georgetown	1.6	216	16	203	15
Rhinelander	1.9	145	15	172	20

These results indicate that while primary clarification is not a mandatory requirement, there are obviously cases where it is desirable. Whenever high grease concentrations (greater than 100 mg/l hexane soluble fraction (15)) may be encountered, primary clarification should always be used with appropriate skimming devices on the clarifier surface.

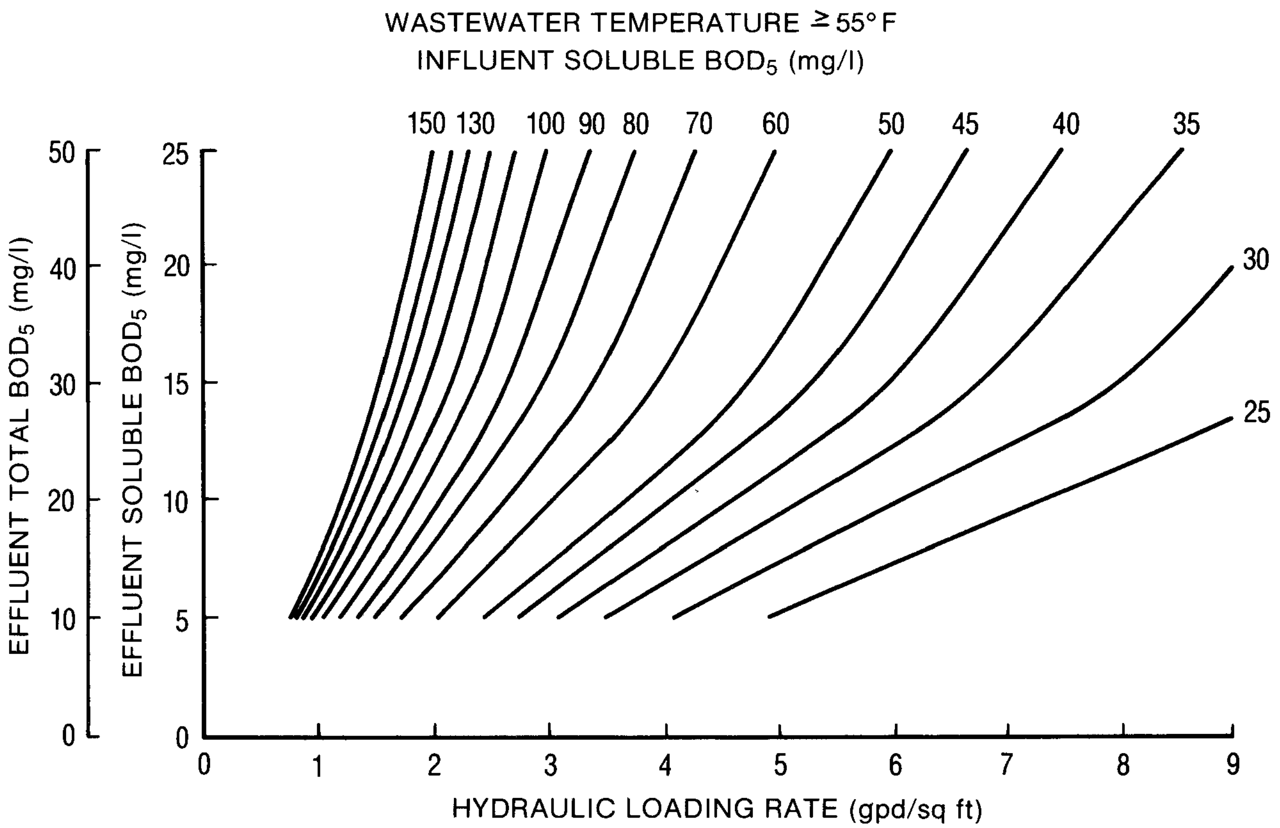


Figure 5-3. Autotrol organic removal design relationships for mechanical drive RBC's [from Autotrol design manual (4)].

Srinivasaraghaven et al. (9) treated primary effluent in a four-stage, 10.4-ft diameter air driven RBC. The hydraulic loading ranged from 1 to 3 gpd/sq ft, and although low effluent soluble BOD_5 values were always obtained they were always higher than predicted by the Autotrol curves (4) for air driven units (not shown in this report, but predict slightly higher allowable loadings for given effluent BOD_5 concentrations than the mechanical drive curves in Figure 5-3). Observed and predicted soluble values are shown below:

Parameter	Phase 1	2	3	4	5	6	7
Observed Effluent $SBOD_5$ (mg/l)	9	8	7	12	9	9	8
Predicted Effluent $SBOD_5$ (mg/l)	7	5	5	7	5	5	5

Full-scale RBC studies conducted at Alexandria, Virginia (16), compared mechanical drive units with and without supplemental air addition utilizing primary effluent feed that averaged 32 mg/l soluble BOD_5 over 150 days of data collection. For this mechanical drive system, an overall system loading up to 1 lb soluble BOD_5/day/1000 sq ft would still meet Autotrol's recommended limit to the first stage of 4 lb soluble BOD_5/day/1000 sq ft. The 30- to 40-mg/l soluble BOD_5 concentrations typically encountered in the influent would correspond to hydraulic loadings of 3 to 4 gpd/sq ft (at 1 lb soluble BOD_5/day/1000 sq ft overall). The Autotrol design curves (Figure 5-3) predict soluble effluent BOD's of 5 mg/l resulting in 83- to 87-percent total BOD_5 removals. These predictions can be compared to measured soluble BOD_5 removals of less than 50 percent of the soluble BOD_5 applied in the loading range in which the Autotrol curves are applicable. The measured effluent soluble BOD_5 values averaged three to four times higher than the predicted values. Removals in the supplemental air system were substantially better because of biofilm thickness control.

It is concluded from the above cited studies that the inherent simplicity offered by using any manufacturers' empirical design curves for organic removal should be tempered with the realization that they are not always accurate and in some cases can substantially overestimate attainable removals. This discrepancy is to be expected since it is highly unlikely any set of universal design curves will ever be developed that predict RBC effluent quality as a single-valued function of some design parameter for all wastewaters. Available data suggest that the manufacturers' design curves be used with caution whenever first-stage loadings exceed 2.5 lb soluble BOD_5/day/1000 sq ft (5 to 6 lb total BOD_5/day/1000 sq ft). These data also indicate that the effluent total-to-soluble BOD_5 ratio for RBC's may often exceed 2.0. Predictions of suspended BOD removal in the final clarifier should be based on clarifier overflow rates and not an automatic doubling of predicted effluent soluble BOD.

5.4.3 An Alternative Design Approach (Second-Order Kinetics)

A number of empirical models have been developed and are currently being used by manufacturers and others for predicting the organic removal performance of RBC's. In attempting to devise a method for improved performance estimation, Opatken (17) inserted soluble organics interstage data (18)(19) into a second-order kinetic expression and found good correlation between the rate of disappearance of soluble organics with the square of the concentration. Field data were then collected on interstage soluble COD (SCOD) at three RBC facilities. The data from two of these facilities correlated well with the second-order kinetic expression. There were indications of inadequate oxygen transfer at the third facility, and the removal rate of SCOD for this system appeared to be oxygen transfer rate limited rather than biochemical reaction rate limited. The reaction rate for the third plant simulated zero-order removal of soluble organics rather than second-order removal. A similar conclusion was reached by Opatken in assessing data generated by Hynek and Chou (19) on an RBC system where the hydraulic loading was doubled, i.e., the removal rate was zero order rather than second order at the higher hydraulic loadings because of oxygen transfer limitations.

Opatken applied the Levenspiel equation for second-order kinetics (20) to compare predicted interstage and final effluent soluble BOD_5 ($SBOD_5$) values against measured values obtained at nine full-scale, air drive RBC plants (21). The equation utilized for determining the concentration of soluble organics at any stage was:

$$C_n = \frac{-1 + \sqrt{1 + 4kt\,(C_{n-1})}}{2kt} \qquad (5\text{-}1)$$

where C_n is the concentration of soluble organics in the nth stage (mg/l), k is the second-order reaction rate constant (l/mg/hr), t is the average hydraulic residence time in the nth stage (hr), and C_{n-1} is the concentration of soluble organics entering the nth stage (mg/l).

The second order reaction-rate constant, k, used in Equation 5-1 was derived from full-scale, air drive, interstage data generated by Hynek and Chou (19) during a comparative evaluation of air and mechanical drive RBC's. The k value so derived is 0.083 l/mg/hr and is assumed by Opatken to be constant when treating municipal wastewaters with RBC's.

The residence time in hours for any stage was calculated from hydraulic loading data and application of the volumetric factor of 0.12 gal tank liquid volume/sq ft media surface area. The primary effluent $SBOD_5$ concentration, C_{n-1}, was used as the influent concentration to the first stage to determine the concentration in the first stage. The $SBOD_5$ concentration of the first stage was then used as the influent concentration to the second stage. This mathematical process was then repeated through each ensuing stage.

Measured interstage $SBOD_5$ data for nine air drive RBC systems are compared with predicted interstage concentrations obtained by applying the second-order rate expression and with predicted interstage concentrations obtained by using the Autotrol design curves (4) in Table 5-2. The disappearance of $SBOD_5$ with time is displayed graphically in Figures 5-4 to 5-12 for measured and second-order predicted values.

Good agreement was obtained between second-order predicted and measured $SBOD_5$ concentrations at seven of the nine plants, with substantial differences exhibited at Enumclaw and Lancaster. Opatken (17) modified the analysis of the Lancaster data by assuming an inadequate oxygen transfer rate in the first stage due to the high organic loading and then applying the second-order kinetic equation to the following stages. By using the value of 78 mg/l $SBOD_5$ measured in the first-stage effluent as the initial concentration for the rest of the train and then calculating $SBOD_5$ in the ensuing stages, he was able to obtain good agreement for Lancaster between second-order predicted and measured $SBOD_5$ concentrations. No plausible

TABLE 5-2. COMPARISON OF MEASURED, SECOND-ORDER PREDICTED, AND AUTOTROL DESIGN MANUAL PREDICTED DISAPPEARANCE OF $SBOD_5$ FOR AIR DRIVE RBC SYSTEMS

Cleves, Ohio

Shafts/Stage = 1-1-1

Time/Stage (hr) = 2.5, 2.5, 2.5

	Measured	Predicted: Second Order	Predicted: Autotrol Design Manual
C_{in} =	40	40	40
C_1 =	8	12	<5
C_2 =	5	5	
C_3 =	3	3	

Enumclaw, Washington

Shafts/Stage = 3-1-1-1

Time/Stage (hr) = 1.4, 0.46, 0.46, 0.46

	Measured	Predicted: Second Order	Predicted: Autotrol Design Manual
C_{in}^* =	168	168	168†
C_1^* =	14	34	
C_2^* =	9	20	
C_3^* =	7	13	
C_4^* =	6	10	

Lancaster, Wisconsin

Shafts/Stage = 1-1-1-1.5**

Time/Stage (hr) = 1.4, 1.4, 1.4, 2.2

	Measured	Predicted: Second Order		Predicted: Autotrol Design Manual
C_{in} =	218	218		218†
C_1 =	78	39	78††	
C_2 =	22	15	22	
C_3 =	14	8	10	
C_4 =	8	4	5	

Lower East Fork, Ohio

Shafts/Stage = (3-2-2-2)**

Time/Stage (hr) = 0.97, 0.64, 0.64, 0.64

	Measured	Predicted: Second Order	Predicted: Autotrol Design Manual
C_{in} =	20	20	20†
C_1 =	11	11	<5
C_2 =	6	8	
C_3 =	5	6	
C_4 =	5	5	

(continued)

TABLE 5.2 (continued)

Woodburn, Washington

Shafts/Stage = 4-2-1.5**-1.5**

Time/Stage (hr) = 1.69, 0.84, 0.63, 0.63

	Measured	Predicted: Second Order	Predicted: Autotrol Design Manual
C_{in} =	226	226	226†
C_1 =	28	37	
C_2 =	7	17	
C_3 =	7	11	
C_4 =	7	8	

Glenwood Springs, Colorado

Shafts/Stage = 1-1-1-1.5**

Time/Stage (hr) = 0.56, 0.56, 0.56, 0.84

	Measured	Predicted: Second Order	Predicted: Autotrol Design Manual
C_{in} =	43	43	43
C_1 =	20	22	13
C_2 =	14	13	<5
C_3 =	4	9	
C_4 =	5	6	

Dodgeville, Wisconsin

Shafts/Stage = 2-1-1

Time/Stage (hr) = 2.6, 1.3, 1.3

	Measured	Predicted: Second Order	Predicted: Autotrol Design Manual
C_{in} =	37	37	37
C_1 =	9	11	<5
C_2 =	7	7	
C_3 =	4	4	

West Dundee, Illinois

Shafts/Stage = 1-1-1.5**

Time/Stage (hr) = 0.76, 0.76, 1.2

	Measured	Predicted: Second Order	Predicted: Autotrol Design Manual
C_{in} =	101	101	101
C_1 =	33	33	>25
C_2 =	15	16	10
C_3 =	8	9	<5

(continued)

TABLE 5.2 (continued)

Hartford, Michigan

Shafts/Stage = 1-1-1-1

Time/Stage (hr) = 0.25, 0.25, 0.25, 0.25

		Predicted	
	Measured	Second Order	Autotrol Design Manual
C_{in} =	17	17	17†
C_1 =	13	13	-
C_2 =	12	11	-
C_3 =	9	9	<5
C_4 =	8	8	

*C_{in}, C_1, C_2, C_3, and C_4 are $SBOD_5$ concentrations (mg/l) in the reactor influent and first, second, third, and fourth stages, respectively.

†Outside influent $SBOD_5$ limits (30 to 150 mg/l) given in Autotrol air drive design curves, Figure C-1A (4).

**High density media.

††Assume first stage is overloaded and determine concentrations of $SBOD_5$ in succeeding stages based on measured C_1 value.

explanation was offered by Opatken for the observed discrepancy at Enumclaw. An analysis similar to Lancaster was not considered to be valid because the measured concentration of $SBOD_5$ in the first stage was considerably below the second-order predicted value, and, therefore, oxygen transfer at Enumclaw could not have been limiting. The interstage concentrations predicted with the Autotrol design curves (4) are consistently lower than the measured values.

The above empirical data indicate that Levenspiel's second-order kinetic expression may offer an improved basis for predicting interstage soluble organic removals in RBC systems. The lack of published, full-scale interstage data for proprietary equipment other than Autotrol air drive units

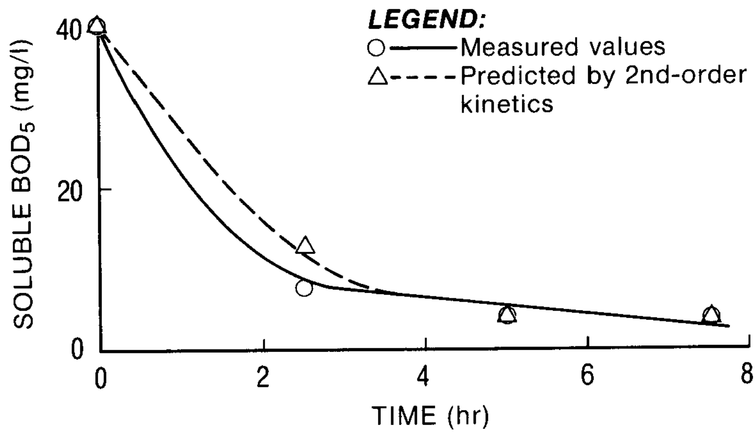


Figure 5-4. Disappearance of soluble BOD_5 with time at Cleves.

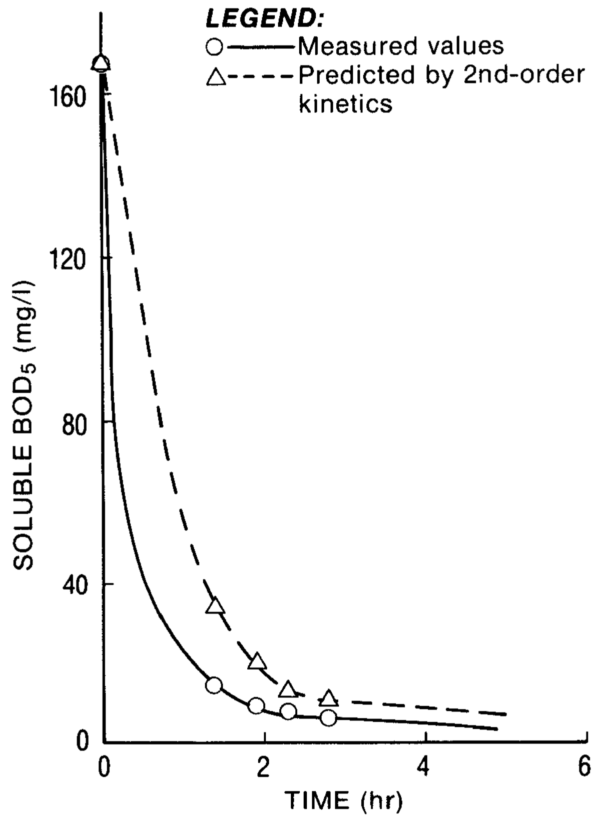


Figure 5-5. Disappearance of soluble BOD_5 with time at Enumclaw.

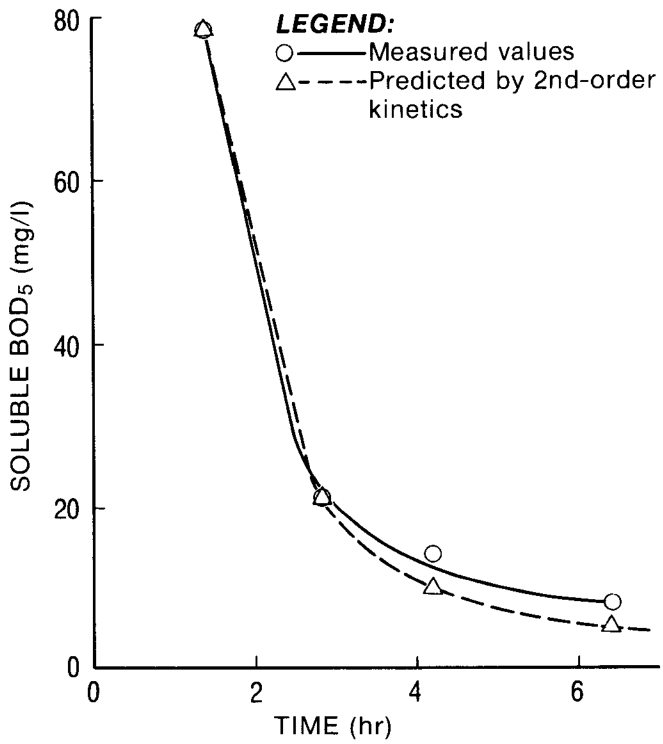


Figure 5-6. Disappearance of soluble BOD_5 with time at Lancaster.

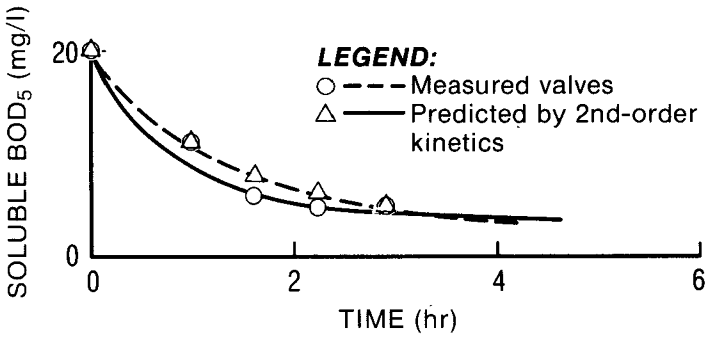


Figure 5-7. Disappearance of soluble BOD_5 with time at Lower East Fork.

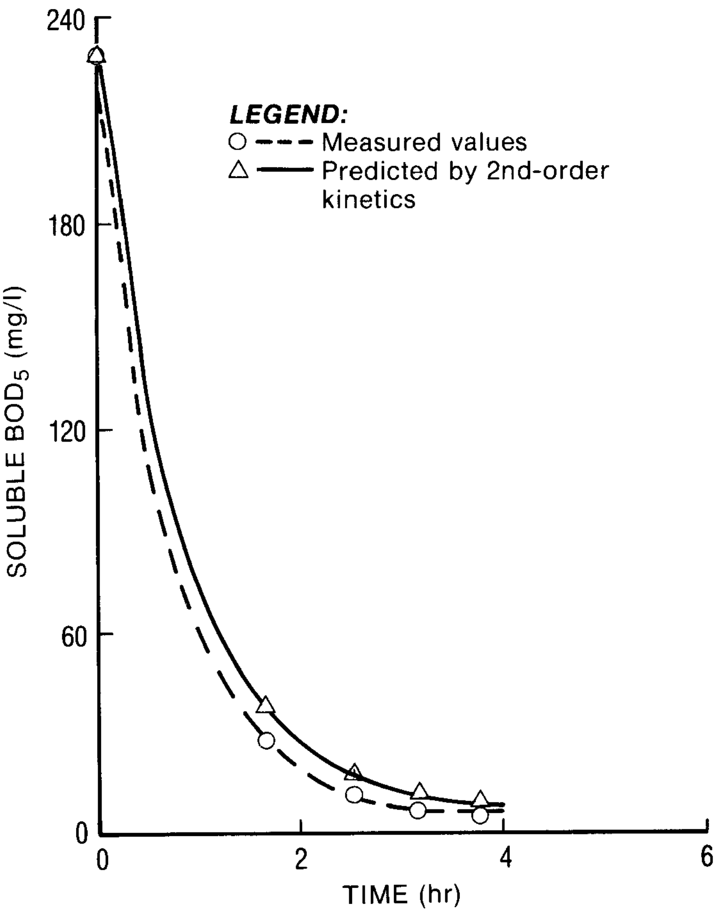


Figure 5-8. Disappearance of soluble BOD_5 with time at Woodburn.

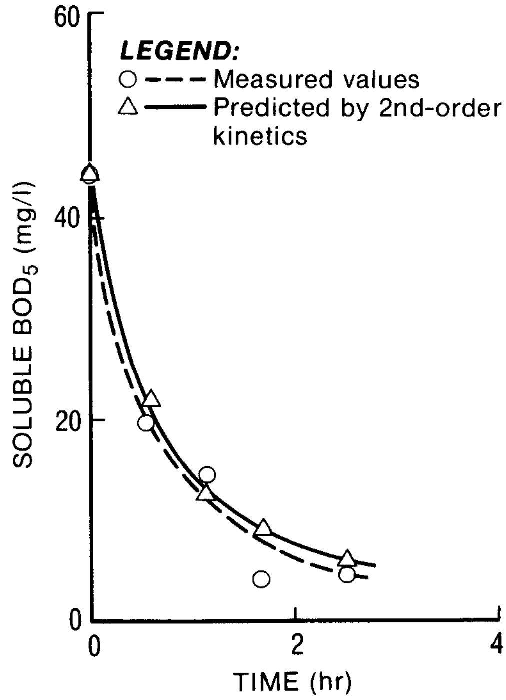


Figure 5-9. Disappearance of soluble BOD_5 with time at Glenwood Springs.

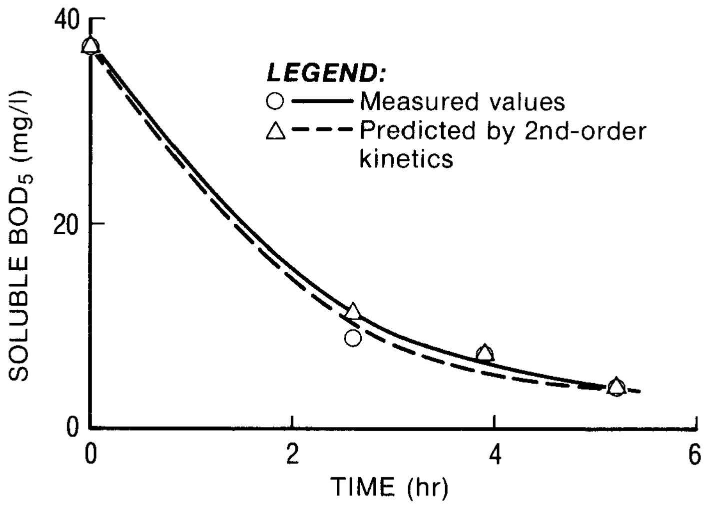


Figure 5-10. Disappearance of soluble BOD_5 with time at Dodgeville.

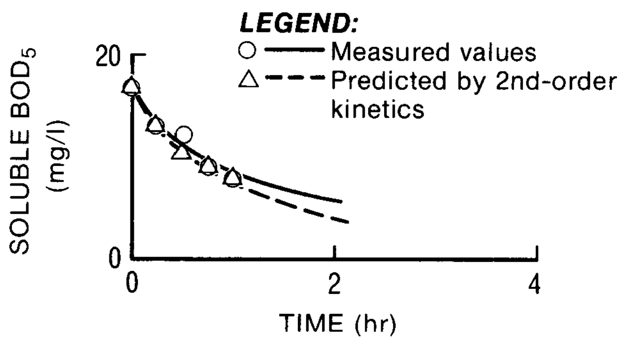


Figure 5-12. Disappearance of soluble BOD_5 with time at Hartford.

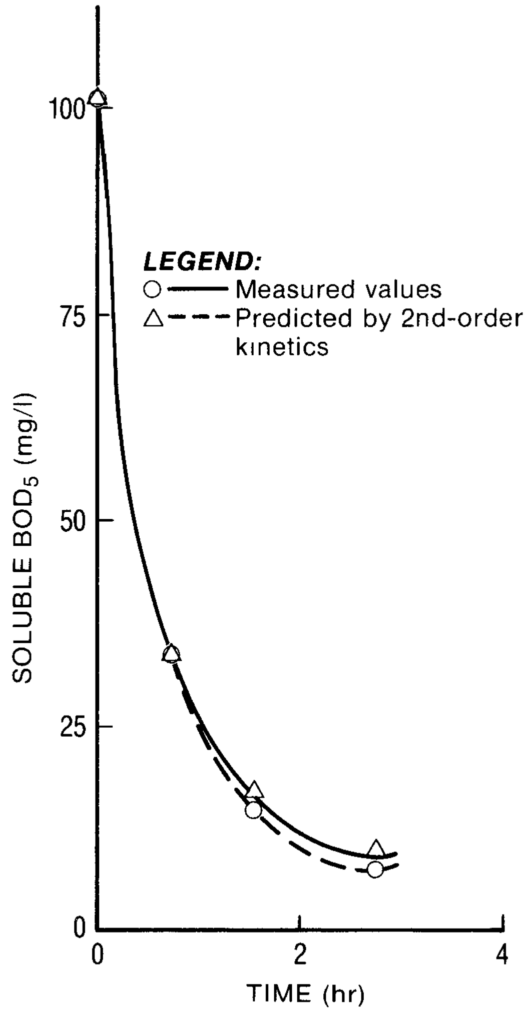


Figure 5-11. Disappearance of soluble BOD_5 with time at West Dundee.

prevents comparison of the second-order technique with other empirical models. The utility of the second-order kinetic procedure described herein should continue to be evaluated for both mechanical and air drive RBC options as additional interstage data become available.

5.5 Nitrification Design

5.5.1 Comparison of Available Empirical Design Approaches

Published empirical procedures are available for RBC nitrification design from the same four manufacturers, Autotrol (4), Clow (5), Lyco (7), and Manufacturer X (6), cited under organic removal design (Section 5.4.1). RBC nitrification systems are also marketed by Crane-Cochrane and Walker Process, but published design methods were not available for these firms at the time of this writing (September 1982).

As with organic removal design, most RBC nitrification design recommendations vary considerably from manufacturer to manufacturer. Organic influent contraints where the recommended nitrification design procedures become applicable, however, are similar for all four: 15 mg/l soluble BOD_5 or less for Autotrol, Clow, and Manufacturer X and 30 mg/l total BOD_5 or less for Lyco. Manufacturer recommended temperature correction factors that inflate required media surface area for nitrification at wastewater temperatures below 55^oF were shown previously in Figure 2-10.

In terms of internal staging, Clow recommends a minimum of four stages and indicates that the addition of two more stages will increase nitrification efficiency by 5 percent. Autotrol states that staging in its predicted zero-order removal range, i.e., bulk liquid ammonia nitrogen concentrations of 5 mg/l and above, is ineffective and unnecessary. Autotrol does recommend staging in the first-order zone of removal, i.e., below 5 mg/l NH_3-N. Lyco separates staging requirements into two categories: separate-stage nitrification and combined carbon oxidation-nitrification. In the former case, staging recommendations are identical to those for BOD_5 removal: one stage for up to 40 percent NH_3-N removal, two stages for 35 to 65 percent removal, three stages for 60 to 85 percent removal, and four stages for 80 to 95 percent removal. For the latter case, a minimum of four stages is recommended. Staging for nitrification was not addressed by Manufacturer X.

If peak daily flow is not anticipated to exceed average daily flow by a factor of more than 2.5, Autotrol and Clow recommended using average flow for design. Lyco indicates RBC systems are resistant to peaking and provides no specific guidelines. Manufacturer X advised using average daily flow for design, without specific reference to a peak flow factor.

To permit convenient comparison, all four of the above empirical design methods were translated to a common predictive basis: effluent ammonia nitrogen concentration versus applied hydraulic loading (3). Four comparative plots are presented in Figures 5-13, 5-14, 5-15, and 5-16, for influent ammonia nitrogen levels of 10, 15, 20, and 30 mg/l, respectively. It was necessary to extrapolate between influent concentrations provided on Lyco's basic design curves (7) to construct the portions of the comparative figures applicable to that firm. In the case of Clow, the midpoint of the loading ranges given for each design effluent concentration (5) was used in developing its curves in the comparative figures.

Utilization of Figures 5-13 to 5-16 for separate-stage nitrification is straightforward. The procedure is somewhat more involved for sizing combined carbon oxidation-nitrification RBC systems. Each manufacturer's procedure in the latter design application is or was based on first determining the required media surface area to reduce the incoming organic concentration to a prescribed level: 15 mg/l soluble BOD_5 for Autotrol, Clow, and Manufacturer X and 30 mg/l total BOD_5 for Lyco. Carbonaceous media requirements for the lead portion of the combined reactor should be estimated separately for each manufacturer using its recommended design methods. Figure 5-1, presented earlier in Section 5.4.1, compares mechanical drive carbonaceous media requirements for the several manufacturers for the case where reactor influent soluble-to-total BOD_5 is assumed to be 0.5.

The next step is to determine media surface requirements for the nitrification section of the reactor. The influent ammonia nitrogen concentration to the first carbonaceous stage, not the ammonia nitrogen concentration at the stage where nitrification is presumed to begin, is used by all four manufacturers for this purpose. The required media surface area estimated for nitrification is then added to the carbonaceous media requirement to yield overall system design surface area.

If the effluent target is for a soluble BOD_5 of less than 15 mg/l, an additional step is necessary. Autotrol and Clow recommend checking back to their respective carbonaceous design bases to assess whether the lower soluble BOD_5 goal will result in a greater estimated media requirement than the sum of the two surface areas described above. The larger estimate controls the design. Manufacturer X advocated calculating the media required to lower soluble BOD_5 from 15 mg/l to the target level and then adding this surface area to that already determined by summing the above two requirements. Lyco does not address this topic.

Three example nitrification design problems (mechanical drive) were solved using the manufacturers' organic removal design procedures, Figure 5-15 (20 mg/l influent NH_3-N), and the temperature correction curves in Section 2 (Figures 2-8 and 2-10). The first two examples compare RBC combined carbon oxidation-nitrification for two different wastewater temperatures; the

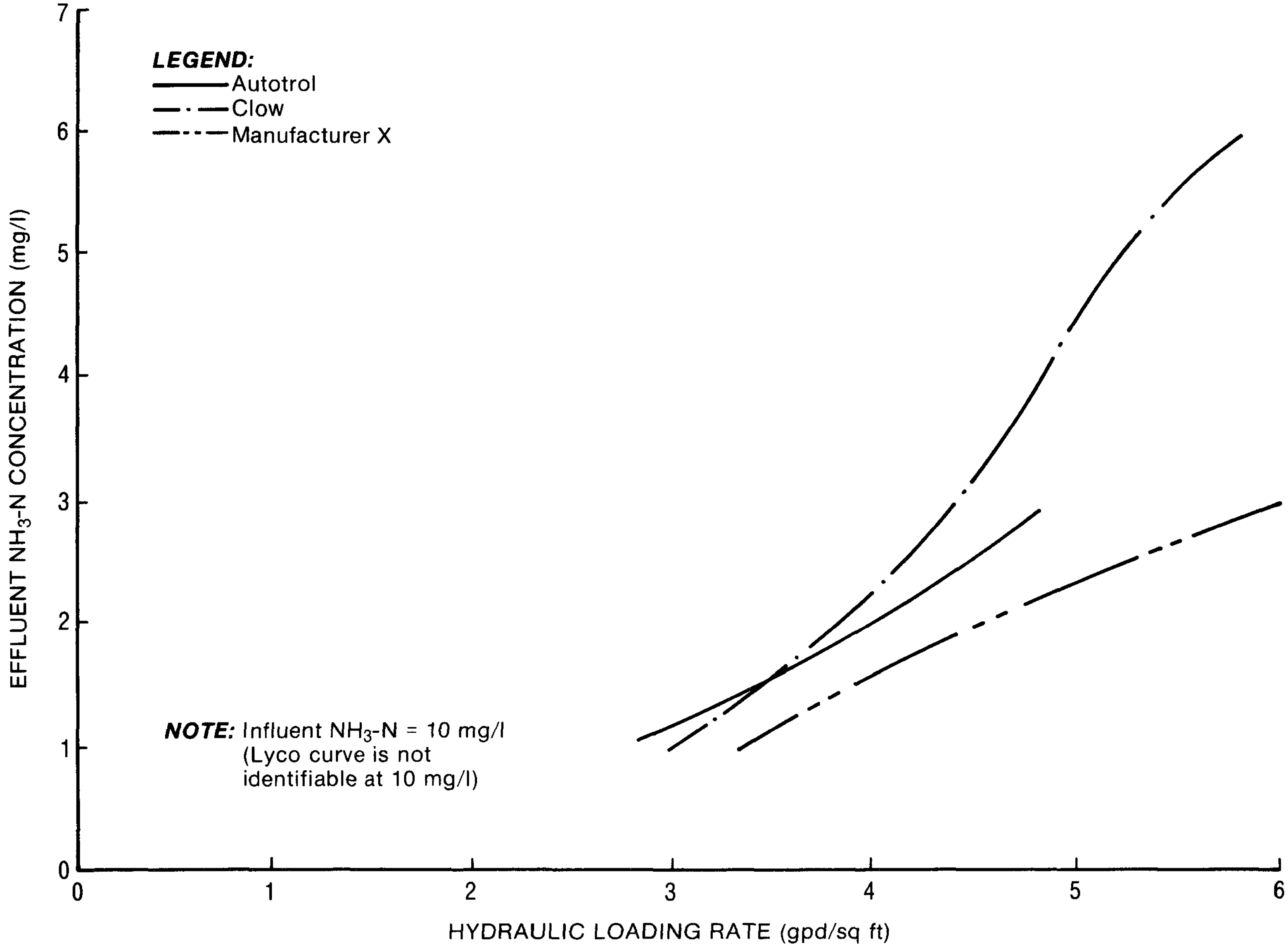


Figure 5-13. Comparative RBC nitrification design curves for an influent ammonia nitrogen concentration of 10 mg/l [from Roy F. Weston (3)].

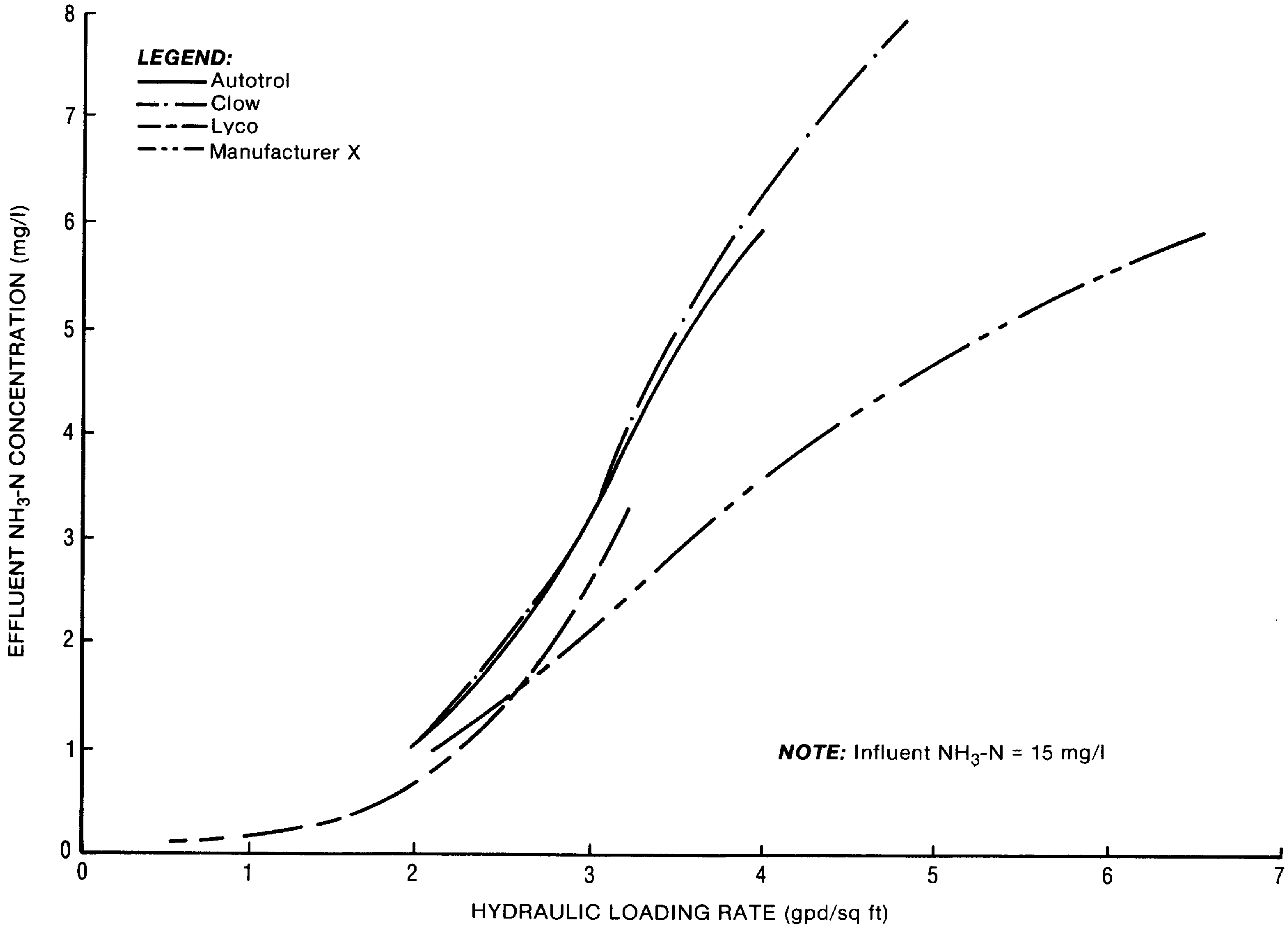


Figure 5-14. Comparative RBC nitrification design curves for an influent ammonia nitrogen concentration of 15 mg/l [from Roy F. Weston (3)].

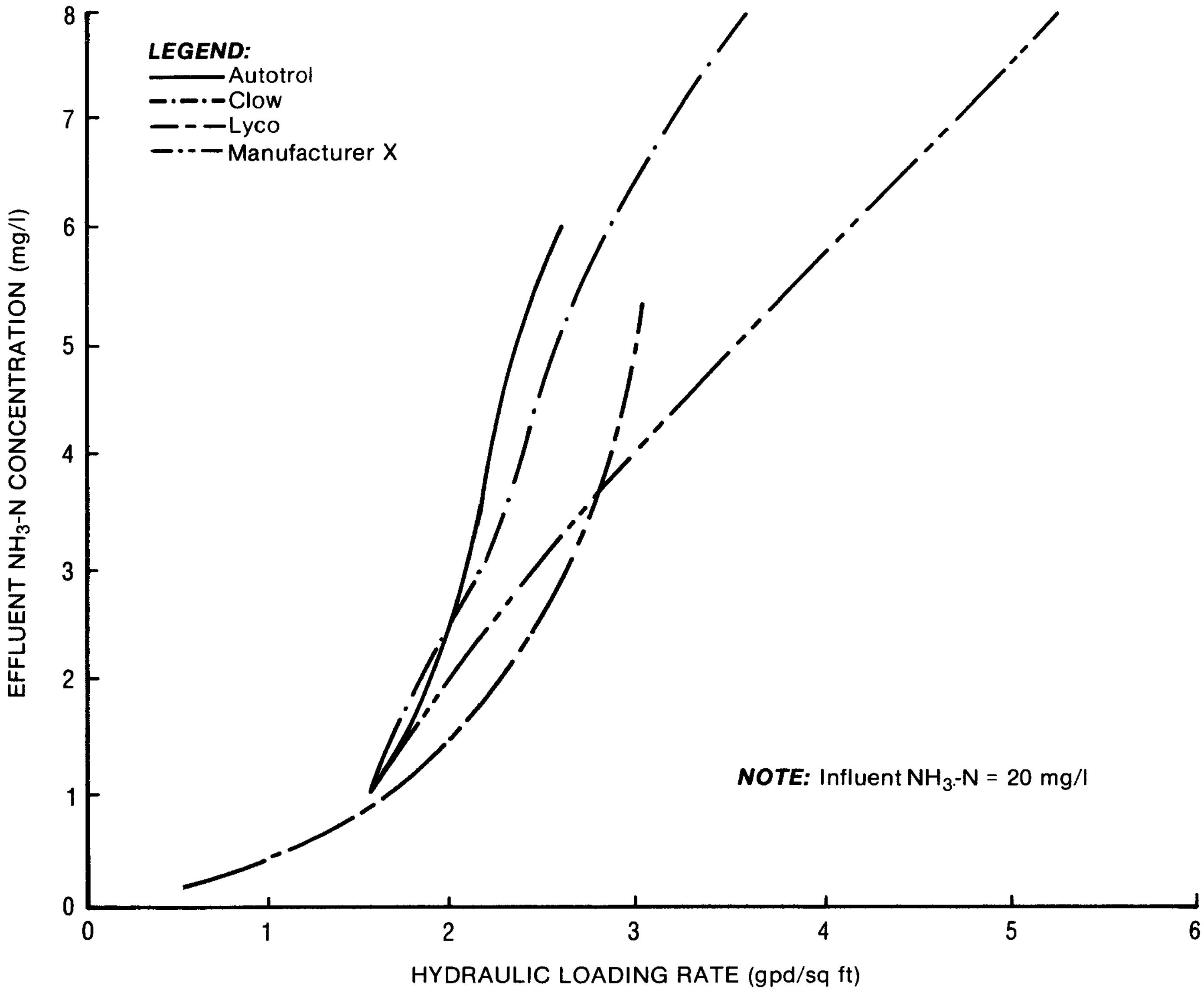


Figure 5-15. Comparative RBC nitrification design curves for an influent ammonia nitrogen concentration of 20 mg/l [from Roy F. Weston (3)].

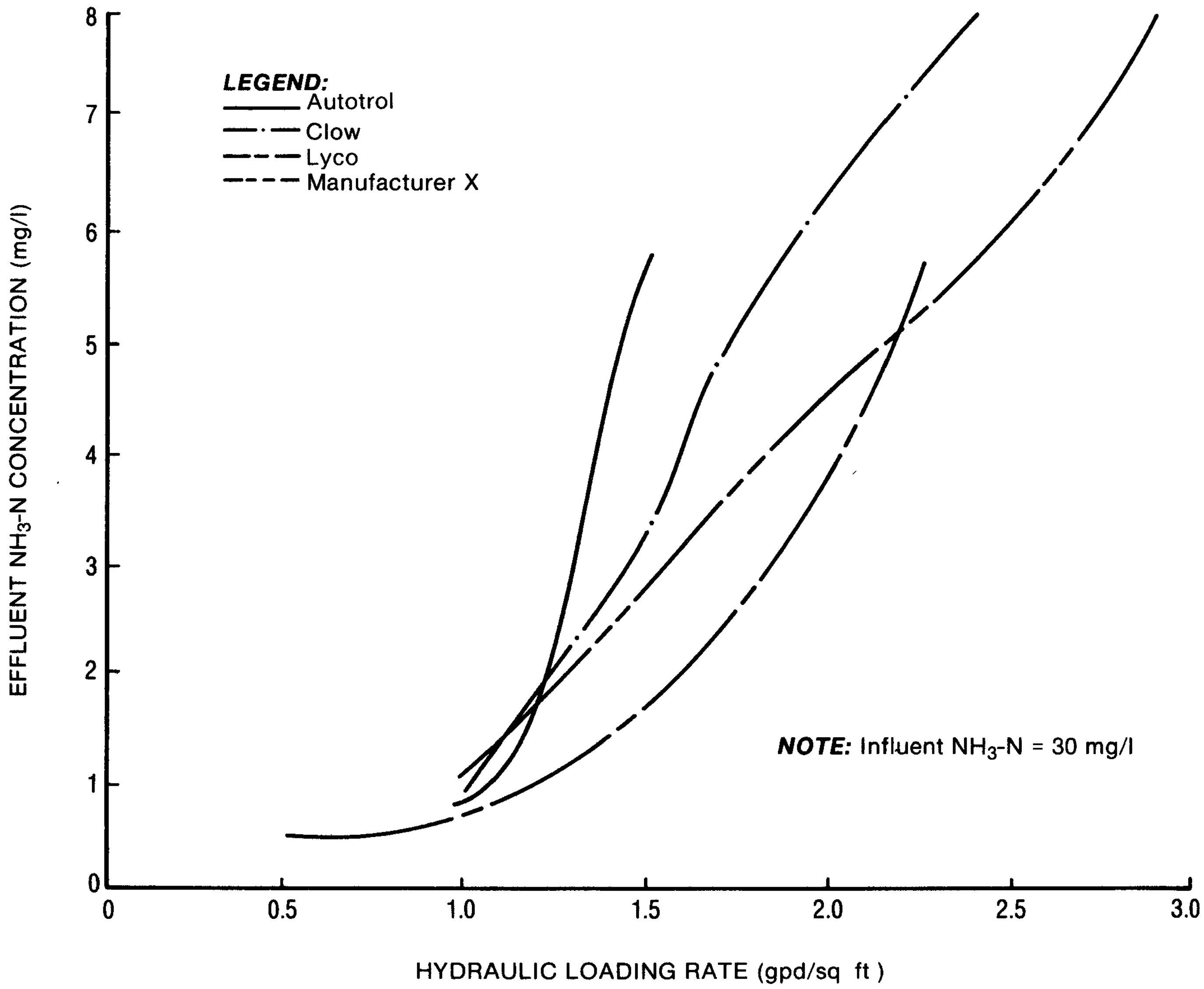


Figure 5-16. Comparative RBC nitrification design curves for an influent ammonia nitrogen concentration of 30 mg/l [from Roy F. Weston (3)].

third encompasses separate-stage RBC nitrification only. Assumed raw wastewater characteristics and the calculated required media surface areas are summarized in Table 5-3.

Carbonaceous media requirements for Lyco in Example Nos. 5 and 6 are extrapolated values since the assumed raw wastewater and primary effluent characteristics fall outside the band of its total BOD_5 design curves.

TABLE 5-3. WASTEWATER PARAMETERS AND REQUIRED MEDIA SURFACE AREAS FOR EXAMPLE RBC NITRIFICATION DESIGN PROBLEMS

Parameter	Design Example No. 5	6	7
Average flow (mgd)	1.0	1.0	1.0
Raw wastewater $TBOD_5$ (mg/l)	125	125	<30*
Raw wastewater $SBOD_5$ (mg/l)	50	50	<15*
Raw wastewater NH_3-N (mg/l)	20	20	20
Wastewater temperature (^oF)	55	45	55
Required $TBOD_5$ removal (%)	85	85	-
Required NH_3-N removal (%)	90	90	90
Effluent $TBOD_5$ (mg/l)	18.8	18.8	-
Effluent $SBOD_5$ (mg/l)†	9.4	9.4	-
Effluent NH_3-N (mg/l)	2.0	2.0	2.0
Primary clarifier $TBOD_5$ removal (%)	30	30	N/A

Design Example No.	Required Media Surface Area (sq ft x 1000) Autotrol(4)	Clow(5)	Mfr X(6)	Lyco(7)
5	742	745	667	687
6	1193	1215	1175	1375
7	532	538	500	431

* Denotes concentration entering RBC separate-stage nitrification reactor.
† Based on an assumed $SBOD_5$:$TBOD_5$ ratio of 0.5 in the final effluent.

Surface area requirements calculated using the four manufacturers' procedures are in close agreement ($\pm$ 10 percent) only for Example No. 5. Significant variability is evident for the low wastewater temperature problem (Example No. 6), indicating the lack of uniformity in low temperture correction factors for nitrification.

The above examples are intended only to illustrate RBC nitrification media sizing techniques employed by the equipment vendors and the degree of variability among techniques that can reasonbly be expected. The solution of actual design problems, although ultimately the responsibility of the design engineer, should include consultations with one or more manufacturers to utilize their experience concerning such factors as unusual wastewater characteristics, atypical flow variations, pretreatment options, possible staging arrangements, standard density/high density media split, etc.

5.5.2 Analysis of Available RBC Nitrification Data

5.5.2.1 Observed Pilot-Scale Removals

Pilot studies have been employed to generate RBC nitrification performance data, both for research purposes and to aid in the design of site-specific full-scale facilities. Borchardt et al. (22) evaluated the effect of a broad range of loadings on both interstage and overall removals in a 4-ft diameter, polystyrene, six-stage pilot unit at Saline, Michigan. This system was operated in a separate-stage nitrification mode on effluent from Saline, Michigan's high-rate trickling filter plant.

Interstage data generated at Saline are plotted in Figure 5-17 as stage ammonia nitrogen concentration versus the calculated removal rate for that stage. Lower and upper curves bounding the Saline data exhibit maximum ammonia nitrogen removal rates of approximately 0.4 and 0.75 lb/day/1000 sq ft, respectively. No correlation was evident for data collected at different wastewater temperatures.

Antoine (23) conducted separate-stage nitrification studies on five pilot plants in the mid-1970's. His composite removal rate curve, constructed irrespective of temperature, is also shown in Figure 5-17 along with a curve developed at 64°F on a separate-stage, 19.7-in. diameter pilot unit at Guelph, Ontario (24). Antonie's composite curve shows no indication of approaching a maximum zero-order nitrification rate at bulk liquid ammonia nitrogen concentrations above 5 mg/l; the Saline boundary curves and the Guelph curve follow the rapid transition from approximate first-order removal to zero-order removal that is the basis of the current Autotrol design (4)(25). The knees of the Saline and Guelph curves occur at about 5 and 7 mg/l NH_3-N, respectively.

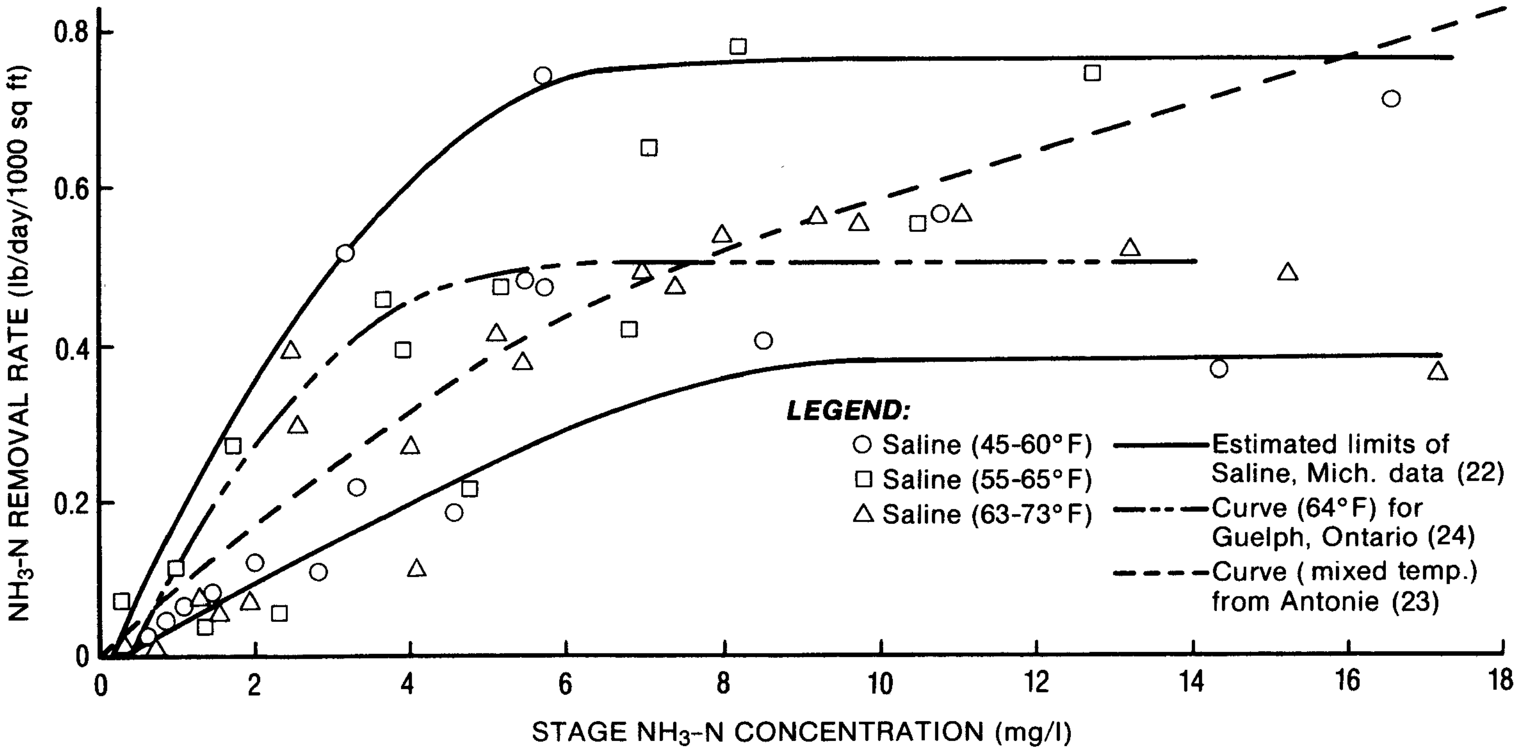


Figure 5-17. Estimated ammonia nitrogen removal rates for pilot-scale, RBC separate-stage nitrification.

Pilot plant data for RBC combined carbon oxidation-nitrification are less numerous. The results of work carried out at Utah State University (26) on 15-in. diameter pilot units are presented in Figure 5-18. Predictive equations based on the Monod relationship were developed with linear regression techniques to fit the plotted data. Based on the relatively few data points provided, a case could also be made for constructing a first order-zero order rapid transition curve of reasonably good fit for the 68°F plot with a knee at approximately 3 mg/l.

The high removal rates observed in RBC separate-stage nitrification pilot studies are repeated in Figure 5-18. In contrast to the non-temperature related data in Figure 5-17, the Utah State data indicate a definite temperature dependence. The maximum ammonia nitrogen removal rate at 68°F approximated 0.65 lb/day/1000 sq ft compared to 0.45 lb/day/1000 sq ft at 59°F.

5.5.2.2 Observed Full-Scale Removals

Available nitrification interstage data at a wastewater temperature of 55 ± 2°F are plotted in Figure 5-19 for three full-scale RBC plants. Gladstone and Cleves are combined carbon oxidation-nitrification systems, while Guelph is a separate-stage nitrification unit treating activated sludge effluent. Gladstone utilizes mechanical drives; Cleves and Guelph are equipped with air drive equipment. All three are Autotrol systems.

Each point in Figure 5-19 represents data for one day for a given stage. For the combined carbon oxidation-nitrification systems, ammonia nitrogen removal data prior to the stage in the train where maximum nitrification rates were observed were omitted on the assumption that organic removal was still heavily influencing nitrifier growth in those stages. An estimated curve drawn through the plotted points essentially duplicates the current Autotrol design curve (25) for a wastewater temperature of 55°F (refer to Figure 2-9). The zero-order removal rate above bulk liquid ammonia nitrogen concentrations of 5 mg/l in Figure 5-19 is projected at 0.3 lb NH_3-N/day/1000 sq ft, the same as the Autotrol design. The knee of the curve is at approximately the same concentration for both curves also.

Nitrification data for five full-scale Autotrol facilities operated at wastewater temperatures in the range of 60 to 70°F are presented in Figure 5-20. All but the Indianapolis facility are combined carbon oxidation-nitrification systems. The Indianapolis data were generated on a 10.5-ft diameter pilot unit and are included in the plot because of the close proximity in media diameter to that of field units.

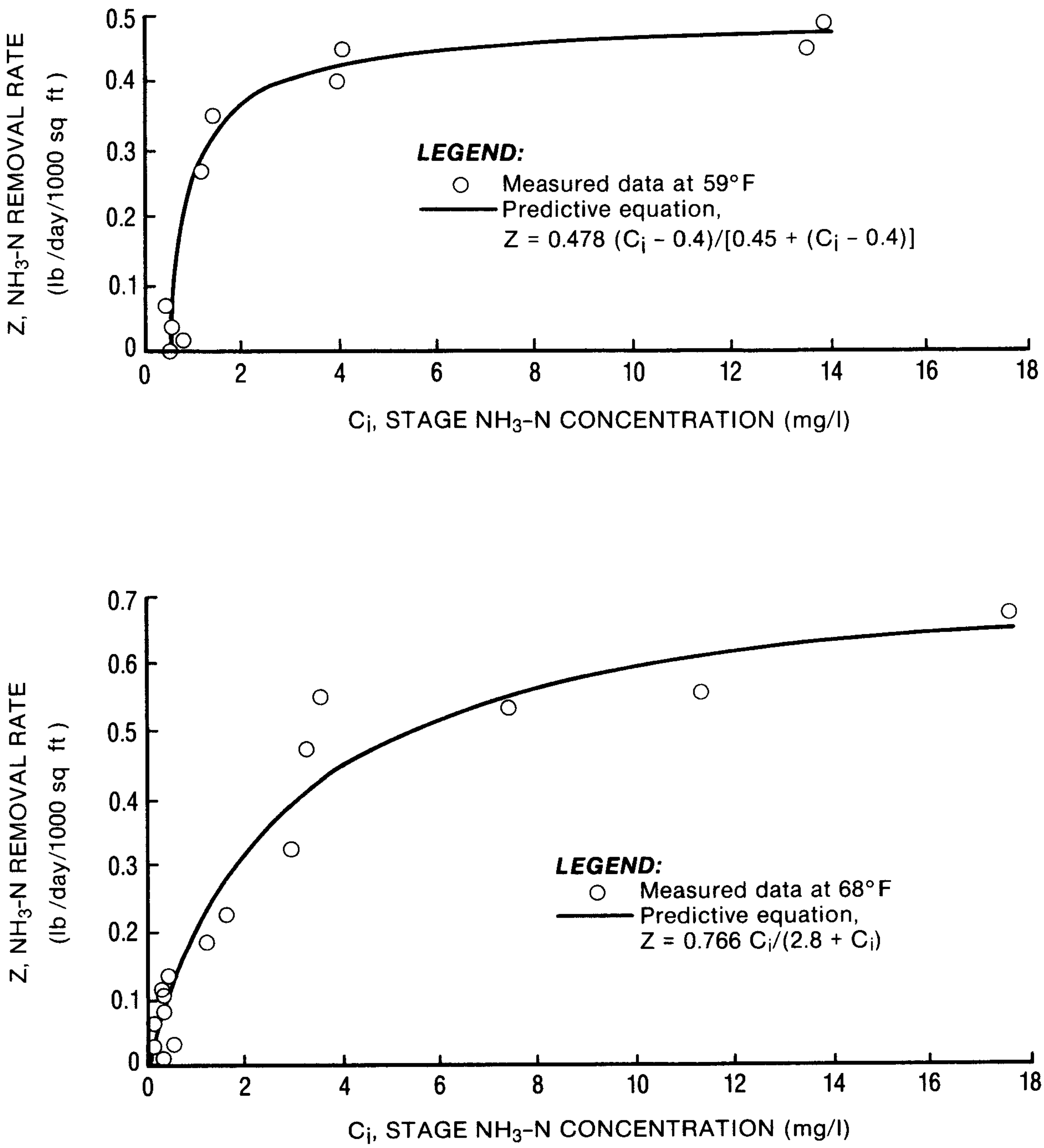


Figure 5-18. Estimated ammonia nitrogen removal rates for pilot-scale, RBC combined carbon oxidation-nitrification [adapted from Pano et al. (26)].

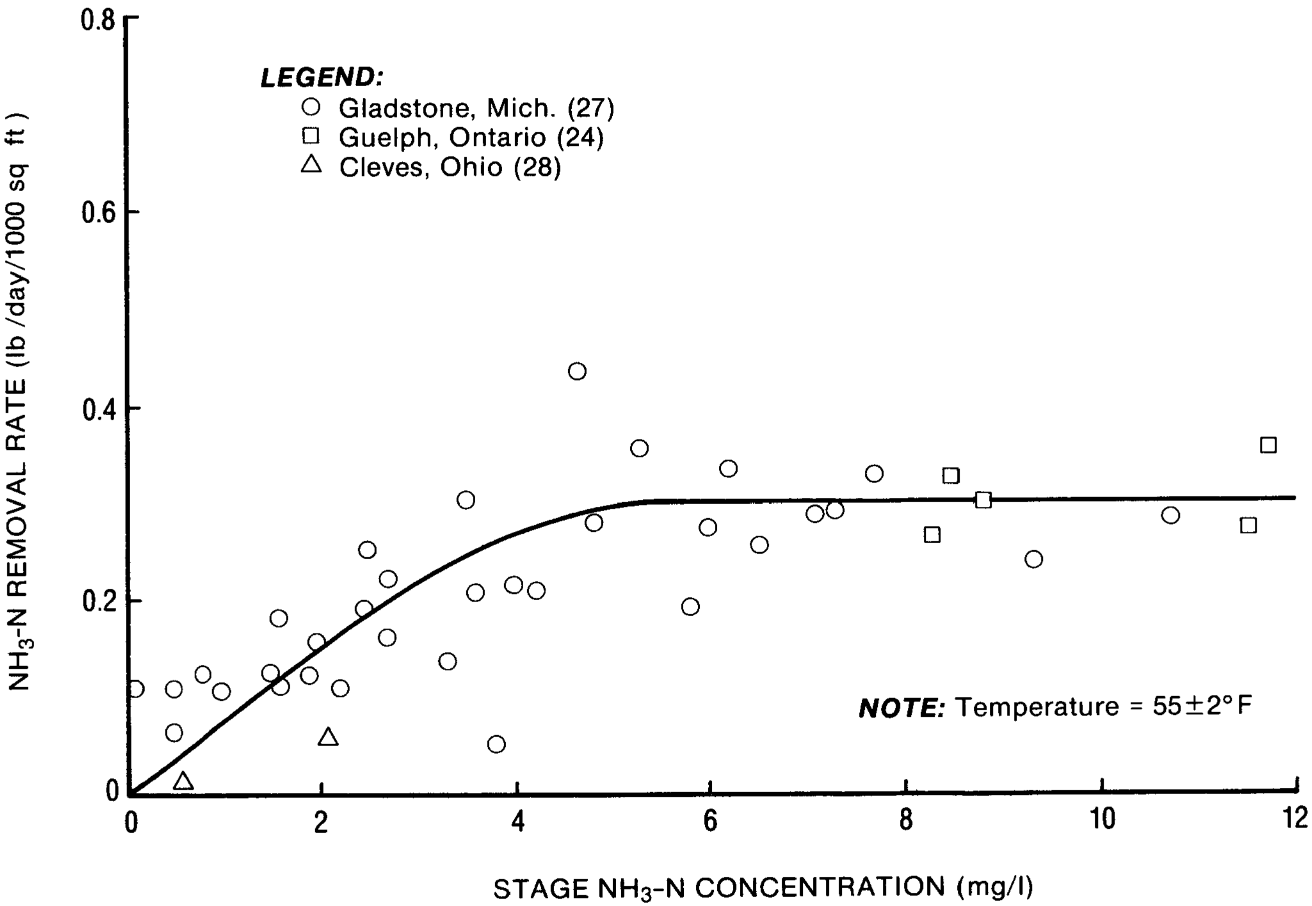


Figure 5-19. Full-scale RBC nitrification rates at design wastewater temperature (55°F).

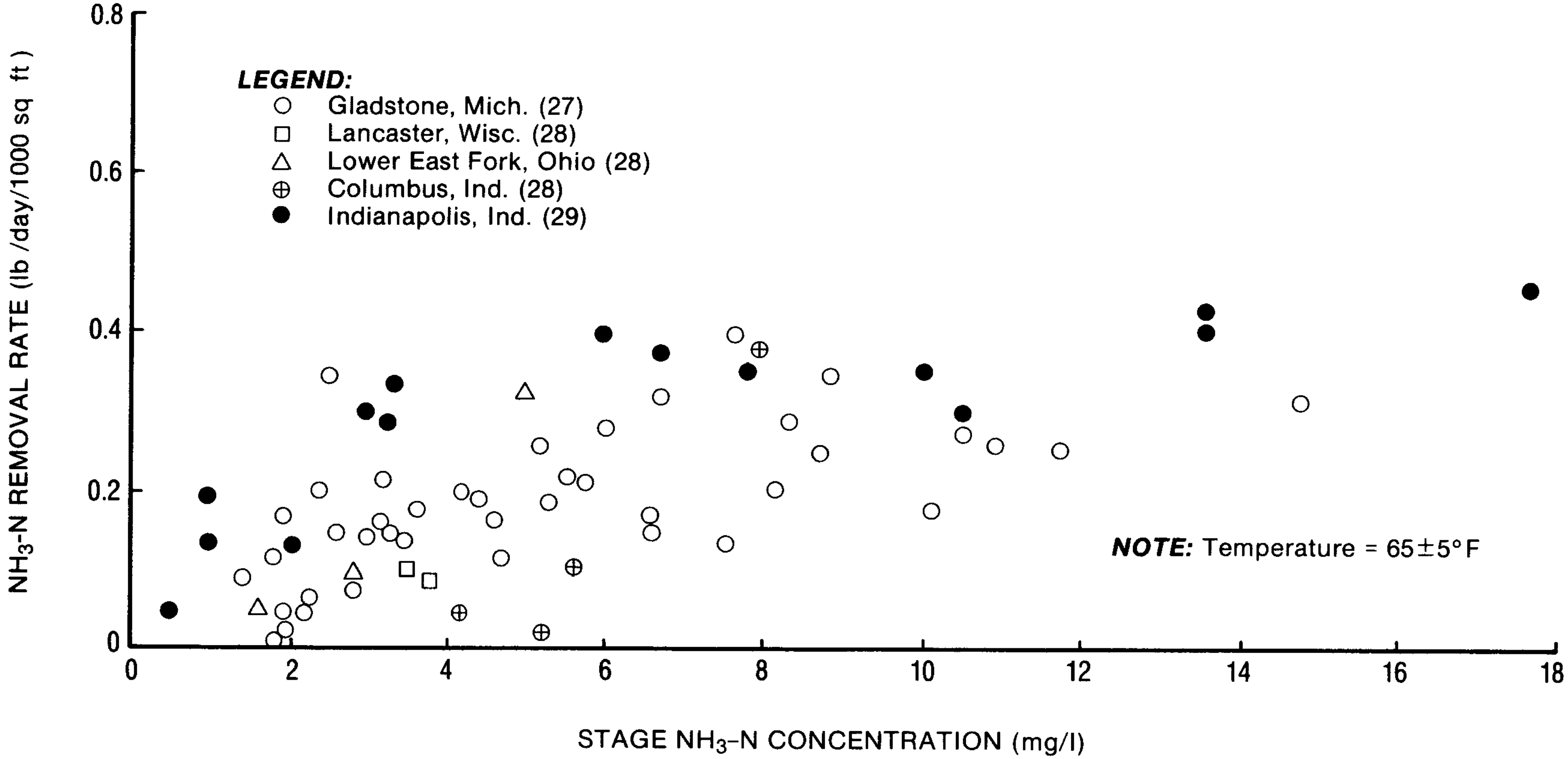


Figure 5-20. Full-scale RBC nitrification rates at high wastewater temperatures.

The data in Figure 5-20 are obviously much more scattered than in the 55 ± 2°F plot (Figure 5-19). No attempt to draw a representative curve through the data was made. The plotted ammonia nitrogen removal rates for the lower bulk liquid stage concentrations are less than those observed at 55 ± 2°F. At higher concentrations, the removal rate roughly centers around 0.3 lb NH_3-N/day/1000 sq ft with widely divergent points above and below. If the Indianapolis data, which were collected at constant flow under carefully controlled pilot conditions, are ignored, the average removal rate above 5 mg/l NH_3-N is well below 0.3 lb NH_3-N/day/1000 sq ft. Considering the data in Figures 5-19 and 5-20, there is no justifiable basis to predict that full-scale RBC peak nitrification rates at temperatures well above 55°F will exceed the maximum design rate at 55°F of 0.3 lb NH_3-N/day/1000 sq ft.

Low temperature (47 ± 2°F) interstage nitrification data from Gladstone are shown in Figure 5-21. These data exhibit an increasing ammonia nitrogen removal rate from the third stage through the sixth stage, suggesting that the low wastewater temperature and perhaps also companion organic concentrations contributed to lower nitrifier development in those stages (4 and 5) where the highest rates would be expected at warmer temperatures. Effluent ammonia nitrogen residuals averaged approximately 9 mg/l for the 6 days represented in Figure 5-21.

The stage-average ammonia nitrogen removal curve plotted for stages 3, 4, 5, and 6 in Figure 5-21 is tilted in the opposite direction from the warmer-temperature plots. The removal or oxidation rate continued to increase through stage 6. It is difficult to determine based solely on an examination of the stage-average curve whether nitrification ever reached its maximum temperature-compatible rate, even in the sixth stage. The following Gladstone data (27) collected at 47 ± 2°F and 55 ± 2°F were compared to further examine this point:

Wastewater Temp. (°F)	No. of Days of Data	Avg. Final Eff. NH_3-N (mg/l)	Avg. NH_3-N Removal Rate (lb/day/1000 sq ft) Stage 3	Stage 4	Stage 5	Stage 6
55 ± 2	11	1.5	0.240	0.310	0.180	0.128
47 ± 2	6	8.9	0.073	0.103	0.170	0.196

The ratio of the maximum removal rates for the two temperatures (stage 4 for 55°F/stage 6 for 47°F) is 1.58. Examination of the temperature correction curve for nitrification (Figure 2-10) reveals that the recommended surface area correction factors for 47°F referred to a base of 55°F range from 1.5 to 1.6 for the four manufacturers represented. This observation provides a measure of indirect evidence that nitrification had reached its temperature-compatible limit in stage 6 for the 47 ± 2°F Gladstone data.

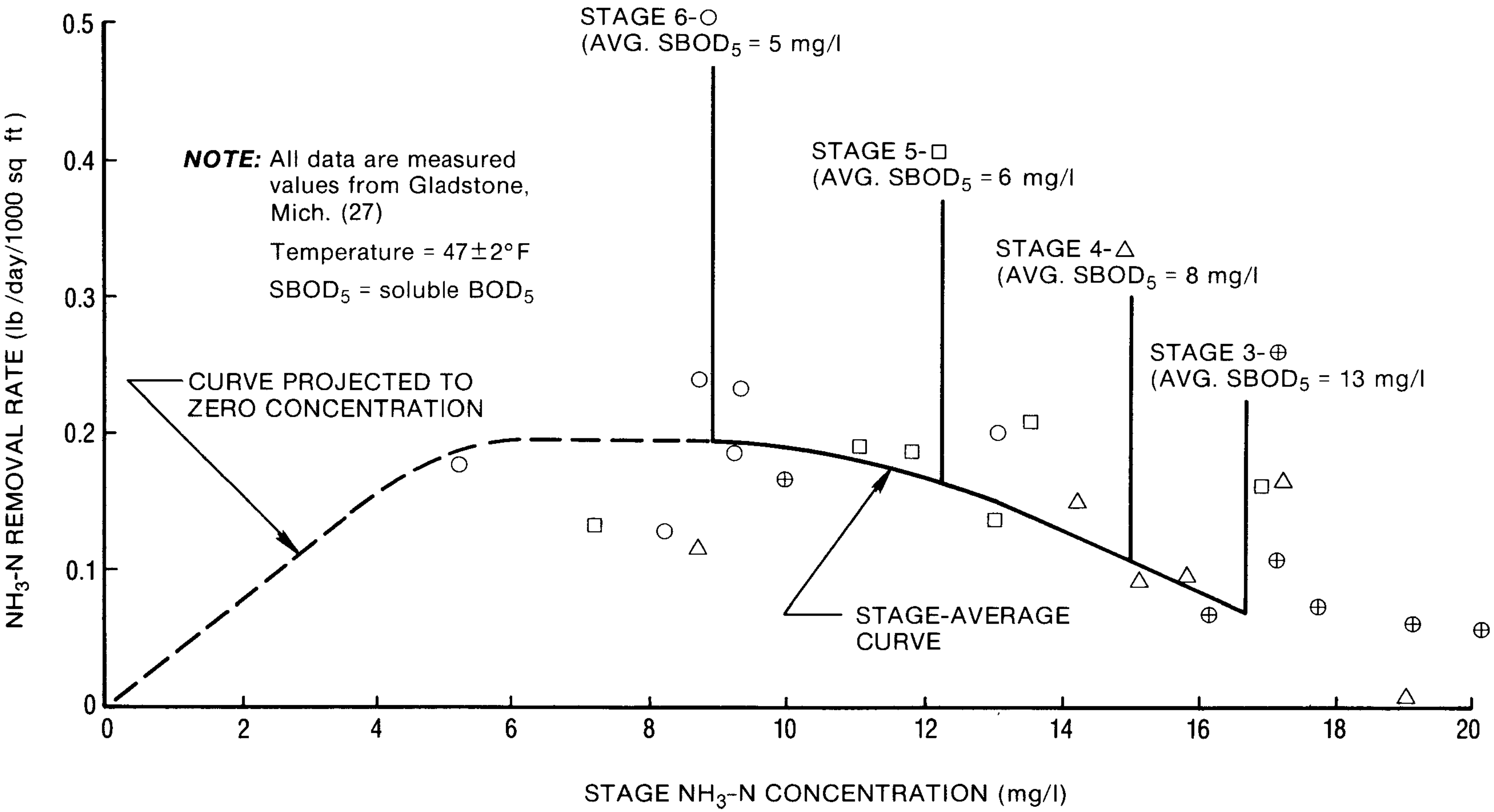


Figure 5-21. Full-scale RBC nitrification rates at low wastewater temperatures.

The Gladstone plant is equipped with 258,000 sq ft of RBC media. If the stage-6 nitrification rate in Figure 5-21 is projected at zero-order removal down to an ammonia nitrogen concentration of 5 mg/l then at first-order removal to zero concentration, the amount of additional media surface area required at 47°F to reach the same 1.5-mg/l effluent residual achieved at 55°F is estimated at about 130,000 sq ft. The surface area correction factor calculated in this manner is 1.50, which would provide approximately 20,000 sq ft less media to reach 1.5 mg/l NH_3-N at 47°F than the 1.58 factor based on a comparison of maximum nitrification rates only. The above exercises support the general applicability of the manufacturers' recommended temperature correction factors for RBC nitrification occurring within the range of 47 to 55°F.

5.5.2.3 Influence of Soluble Organics

The manufacturers' design procedures for nitrification (4)(5)(6)(7) are based on the premise that soluble BOD_5 must be reduced to 15 mg/l or less before significant ammonia nitrogen oxidation can take place in an RBC reactor. Although not implicitly stated, the manufacturers' literature implies that once soluble BOD_5 is reduced to 15 mg/l, nitrification will commence immediately at maximum rates. As shown in Figure 5-21, this is not necessarily the case. The highest nitrification rate was not achieved until the sixth and last stage where the average soluble BOD_5 concentration for the 6 days of 47 + 2°F Gladstone data represented had reached 5 mg/l. The nitrification rate in the third stage (average soluble BOD_5 of 13 mg/l) was less than half that in the sixth stage.

The lag in achieving maximum nitrification rates with decreasing soluble BOD_5 values below 15 mg/l is not restricted to cold wastewater temperatures. The above 47 + 2°F data (February to April 1976) are compared in Table 5-4 with 3 consecutive days of data for Gladstone in August 1976 (27) when the wastewater temperature each day was 68°F. Negligible increase in nitrate nitrogen was observed in stage 2 at 68°F, even though average soluble BOD_5 in that stage was 10 mg/l. The maximum nitrification rate, as indicated by the maximum ammonia nitrogen removal rate, was not reached until stage 4 where soluble BOD_5 had again decreased to 5 mg/l.

The above data suggest that the influence of soluble organic concentration on nitrification rates in RBC's is relatively independent of temperature. As seen by the absolute ammonia nitrogen removal rates and as discussed previously in Section 2.8.4.4, temperature does have considerable impact on the level of nitrification obtained below 55°F. The point at which the maximum rate was observed, however, occurred at the same soluble BOD_5 concentration in both examples. The above discussion is not intended to imply that soluble BOD_5 must be reduced to 5 mg/l to achieve maximum nitrification rates in all situations, but does serve to illustrate that nitrifier-heterotrophic population dynamics continue to play an important role in RBC nitrification down to concentrations substantially less than 15 mg/l $SBOD_5$.

TABLE 5-4. EFFECT OF SOLUBLE BOD_5 ON RBC NITRIFICATION RATES AT GLADSTONE, MICHIGAN

Parameter	Stage 3	Stage 4	Stage 5	Stage 6
2/10-4/15/76 (6 days of data) (47 $\pm$ 2°F)				
$SBOD_5$ (mg/l)	13	8*	6*	5*
NH_3-N (mg/l)	16.7	15.0	12.2	8.9
NO_3-N (mg/l)†	1.4	3.5	6.4	9.5
NH_3-N Removal Rate (lb/day/1000 sq ft)	0.073	0.103	0.170	0.196
†No significant NO_3-N appearance in stage 2 with average $SBOD_5$ = 23 mg/l				
8/12-8/14/75 (3 days of data) (68°F)				
$SBOD_5$ (mg/l)	6*	5*	4*	5*
NH_3-N (mg/l)	13.0	9.5	6.5	4.2
NO_3-N (mg/l)#	1.4	4.5	7.6	10.3
NH_3-N Removal Rate (lb/day/1000 sq ft)	0.199	0.277	0.217	0.179
#No significant NO_3-N appearance in stage 2 with average $SBOD_5$ = 10 mg/l				

*Inhibited $SBOD_5$ values

5.5.2.4 Comparison of Measured Versus Predicted Values for RBC Combined Carbon Oxidation-Nitrification

In addition to extensive interstage sampling conducted at the Gladstone RBC facility by Autotrol, the plant staff has maintained excellent monthly records of plant operation and performance (30). Measured nitrification performance is compared with predicted performance for 2 yr of monthly-average data at Gladstone in Table 5-5. The Autotrol curves (4) utilized in this analysis included Figure 2-8 (temperature correction factors for BOD_5 removal), Figure 2-10 (temperature correction factors for nitrification), Figure 5-3 (organic removal design relationships for mechanical drive units), and Figure 5-22 (nitrification design relationships).

TABLE 5-5. PREDICTED VERSUS MEASURED FINAL EFFLUENT AMMONIA NITROGEN FOR GLADSTONE, MICHIGAN

Month	Pri. Eff. $TBOD_5$ (mg/l)	Pri. Eff. NH_3-N (mg/l)	Hydraulic Loading Rate (gpd/sq ft)	Waste-water Temp. (^oF)	Measured Fin. Eff. NH_3-N (mg/l)	Predicted Fin. Eff. NH_3-N (mg/l)
1977						
Jan.	155	23.9	0.90	47	9.0	*7±
Feb.	144	20.1	1.00	43	7.0	*9±
March	106	14.0	1.33	44	5.6	5.5
April	90	11.6	1.60	47	4.4	2.9
May	121	17.4	1.21	54	3.6	1.2
June	117	19.1	1.04	61	2.1	<1.0
July	94	15.0	1.30	65	1.0	1.1
Aug.	86	12.2	1.57	66	1.0	<1.0
Sept.	93	13.8	1.70	64	1.6	1.6
Oct.	90	11.5	1.64	60	2.0	<1.0
Nov.	76	10.0	2.04	56	2.0	1.2
Dec.	88	13.4	1.52	52	2.7	1.5
1980						
Jan.	77	14.0	1.03	46	1.4	1.1
Feb.	85	17.1	0.90	46	2.0	1.2
March	91	18.4	0.87	46	2.3	1.6
April	88	14.2	1.20	47	2.3	1.7
May	86	17.4	0.98	54	<1.0	<1.0
June	108	15.6	0.96	59	<1.0	<1.0
July	128	15.3	1.00	64	<1.0	<1.0
Aug.	68	14.0	1.01	66	<1.0	<1.0
Sept.	71	16.3	1.00	65	<1.0	<1.0
Oct.	94	18.8	0.89	61	<1.0	<1.0
Nov.	115	19.3	0.80	55	<1.0	<1.0
Dec.	99	18.3	0.77	50	1.5	<1.0

*Values estimated by extrapolation of Autotrol nitrification curves (4), which extend only from 1 to 6 mg/l effluent NH_3-N.

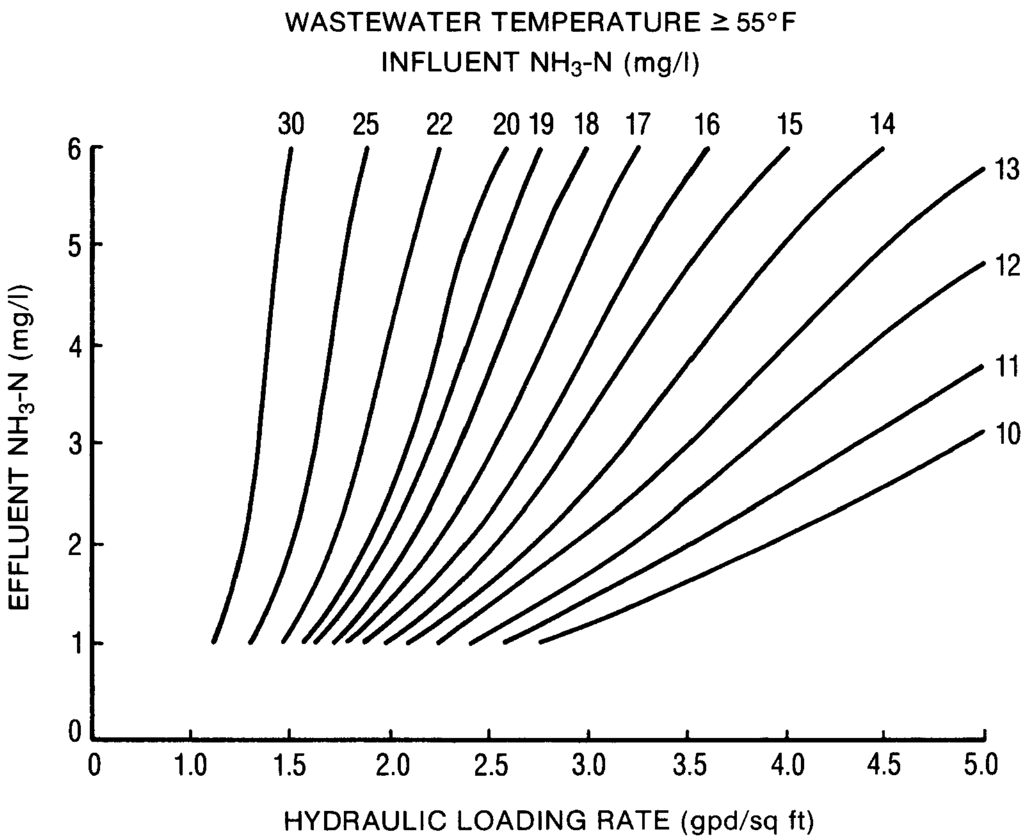


Figure 5-22. Autotrol nitrification design relationships [from Autotrol design manual (4)].

For 1977, primary effluent total BOD_5 averaged 105 mg/l, primary effluent ammonia nitrogen averaged 15.2 mg/l, and the hydraulic loading rate averaged 1.40 gpd/sq ft. The corresponding values for 1980 were 93 mg/l, 16.6 mg/l, and 0.95 gpd/sq ft, respectively.

The Autotrol organic removal curves were developed for use with influent soluble BOD_5 as one of the two input parameters. A primary effluent soluble-to-total BOD_5 ratio of 0.5 was assumed for Gladstone to enable utilization of Figure 5-3. No temperature correction factors were employed for either BOD_5 removal or nitrification for wastewater temperatures $\geq 55^{o}F$.

The predicted final effluent ammonia nitrogen concentrations, although slightly optimistic overall, compare favorably with the measured field values. Considering the assumption made for the primary effluent soluble-to-total BOD_5 ratio, the correlation is excellent. Based on these 2 yr of data from Gladstone, the Autotrol empirical design procedure for combined carbon oxidation-nitrification RBC systems appears to reasonably predict actual performance.

Judging the validity of a design procedure on the basis of one plant can be misleading. Single-day data were provided (27) for three other RBC combined carbon oxidation-nitrification plants: Hartford, Michigan; Lower East Fork, Ohio; and Columbus, Indiana. Predicted and field-measured values for these 3 days of data are summarized below:

Plant	Pri. Eff. $SBOD_5$ (mg/l)	Pri. Eff. NH_3-N (mg/l)	Hydraulic Loading Rate (gpd/sq ft)	Wastewater Temp. (^oF)	Fin. Eff. NH_3-N (mg/l) Measured	Fin. Eff. NH_3-N (mg/l) Predicted
*Hartford	28	17.4	1.98	45	7.5	7.5 $\pm$
†Lower East Fork	19	17.0	1.34	68	1.6	<1.0
#Columbus	27	16.3	1.32	66	4.2	<1.0

*3/16/79, †8/16/79, #4/24/79

Predicted and measured effluent values are in close agreement for two of the above days of data; the Columbus data do not correlate well. The danger inherent in making decisions based on 1 day of information, however, is obvious. Due to the slow response of nitrifiers to changing environmental conditions, it is believed that correlation of predicted and measured concentrations will improve by averaging data over a reasonable time period, provided wastewater temperature does not vary more than 3 to 4^oF during that period.

5.5.2.5 Comparison of Measured Versus Predicted Values for RBC Separate-Stage Nitrification

Very little field data are available that can be used for comparative purposes for this RBC application. Indianapolis (29) conducted a series of separate-stage nitrification evaluations with a 10.5-ft diameter RBC pilot plant. Diurnal flow variations were not imposed. Unchlorinated activated sludge effluent was utilized as system feed. Although the size of the unit employed was somewhat smaller than the 11.5- to 12.0-ft diameter media sold commercially today, it was sufficiently large to be representative of field-scale performance. Predicted and measured average final effluent ammonia nitrogen values for seven phases of the study are presented in Table 5-6. Autotrol's nitrification design curves (Figure 5-22) were used for determining the predicted values.

Correlation of predicted to measured data is reasonably good for four of the seven phases and is not good for the other three. The authors of the Indianapolis pilot study report noted periodic problems with predation in the latter stages of the unit where soluble BOD_5 was routinely re-

TABLE 5-6. PREDICTED VERSUS MEASURED FINAL EFFLUENT AMMONIA NITROGEN FOR INDIANAPOLIS, INDIANA

Phase	Inf. $SBOD_5$ (mg/l)*	Inf. NH_3-N (mg/l)	Hydraulic Loading Rate (gpd/sq ft)	Wastewater Temp. (°F)	Measured Fin. Eff. NH_3-N (mg/l)	Predicted Fin. EFf. NH_3-N (mg/l)
4	9	18.1	1.35	61	6.6	<1.0
5	6	14.0	2.65	59	5.0	1.9
6	3	11.0	2.64	58	1.4	1.1
7	8	14.1	3.00	61	5.7	2.6
8	9	12.1	1.87	67	1.9	<1.0
9	8	8.1	1.79	68	0.5	<1.0
10	10	11.5	2.94	71	1.9	1.9

*Inhibited $SBOD_5$ values

duced to 1 to 3 mg/l. Bypassing of small quantities of primary effluent to the lead RBC stage was reported to reduce predation and improve nitrification efficiency. Whether the higher measured final effluent ammonia nitrogen concentrations (Phases 4, 5, and 7) corresponded to periods of increased predator activity is not known.

5.5.3 Clarification Following RBC Separate-Stage Nitrification

Gravity clarification is obviously required following RBC combined carbon oxidation-nitrification where suspended solids concentrations leaving the reactor are typically several hundred mg/l. The need for clarification and/or the type of clarification following RBC separate-stage nitrification are less clear.

Consider the data (27) shown in Table 5-7 for the Cadillac, Michigan mechanical drive RBC installation that is operated during warm-weather months to nitrify effluent from the City's activated sludge plant. These data indicate that the processes of nitrification and supplemental BOD_5 removal had little effect on suspended solids entering, passing through, and leaving the reactor. The effluent from the last stage would meet most effluent permit requirements.

The ammonia nitrogen loading at Cadillac is fairly low. Higher loadings should have a greater impact on nitrifier growth and sloughing. In such a

TABLE 5-7. PERFORMANCE DATA FROM CADILLAC, MICHIGAN SEPARATE-STAGE RBC NITRIFICATION PLANT

Month	NH_3-N (mg/)		Total BOD_5 (mg/l)		TSS (mg/l)	
	In	Out	In	Out	In	Out*
Aug.'80	6.8	0.5	18	7	17	17
Sept.	2.0	0.4	15	9	30	30
Oct.	2.0	0.2	14	5	20	15
June '81	6.7	0.4	20	7	14	13
July	2.9	0.4	11	4	8	10
Aug.	5.8	0.4	23	5	10	10
Sept.	3.6	0.4	8	6	15	13
Oct.	8.5	0.9	-	-	-	-
Avg.	4.8	0.5	17	6	16	15

*Unclarified suspended solids directly from last reactor stage.

situation, it is likely that additional solids would be generated, but perhaps not to a degree that would necessarily require follow-on clarification. Similarly, the removal of additional BOD_5 (an average 11 mg/l at Cadillac) will also contribute to solids generation and sloughing. These solids will ultimately pass through the system and, in some cases, may have a sufficiently high concentration to warrant removal, although this obviously is not true for Cadillac.

Existing installations employing RBC's for separate-stage nitrification have provided either follow-on gravity clarification or follow-on granular media filtration. It is suggested that clarification of any type not be specified "out-of-hand" for RBC nitrification designs. A comprehensive analysis of the factors affecting this decision should include consideration of anticipated or demonstrated incoming suspended solids, organic carbon, and unoxidized nitrogen loads and their anticipated variability as well as the anticipated removals of these materials, anticipated solids generation, and applicable final effluent limitations.

5.5.4 Summary

Based on the process and design considerations addressed in this document, the following conclusions are offered regarding RBC nitrification:

1. Pilot units (4-ft diameter and smaller) operated at field-equivalent tip speeds of about 60 fpm produce nitrification rates unachievable with full-scale RBC's for valid and explainable reasons.

2. Ammonia nitrogen oxidation in RBC pilot plants exhibits classic Monod response with varying degrees of asymptotic approach to zero- and first-order removal depending on concentration and other pilot study factors.

3. Pilot-scale results generated at or near tip speeds of 60 fpm must be correlated to anticipated full-scale performance through the use of empirically-confirmed scale-up factors or calibration of deterministic models before they can be utilized with confidence for field design.

4. Field-scale RBC's nitrifying at or near 55^{o}F can be described by a dual-kinetic pattern: zero-order oxidation of ammonia nitrogen at approximately 0.3 lb/day/1000 sq ft down to bulk liquid concentrations of roughly 5 mg/l, followed by rapid transition to first-order oxidation thereafter. Additional interstage field data should be collected to further verify this observation.

5. Oxygen transfer capability is the dominant factor controlling full-scale RBC maximum nitrification rates at wastewater temperatures above 55^{o}F and bulk liquid ammonia nitrogen concentrations above 5 mg/l, effectively overriding increased nitrification potential at higher temperatures.

6. Wastewater temperature is the major factor controlling full-scale RBC nitrification below 55^{o}F, becoming increasingly dominant as temperatures of 40^{o}F are approached.

7. Bulk liquid DO's of 3.5 to 4.0 mg/l appear to be sufficient to prevent significant retardation of nitrification rates and efficiency.

8. The potential for achieving enhanced nitrification rates via pH adjustment to pH 8.5 has been shown conclusively at small scale but remains to be demonstrated at full scale.

9. Soluble BOD_5 plays an important role in RBC nitrifier-heterotroph population dynamics down to concentrations of approximately 5 mg/l.

10. Predictability of full-scale effluent ammonia nitrogen concentrations using Autotrol's empirical design approach is good based on very limited data. Additional data sets representing a broader spectrum of plant and climatic conditions need to be evaluated, however, to determine the method's range of applicability. Evaluation of other empirical design procedures will require field-generated interstage performance data on other proprietary equipment.

11. Clarification following RBC separate-stage nitrification should not be mandated as a matter of course, but should be based on a thorough evaluation of all contributing factors.

5.6 Denitrification Design

5.6.1 Introduction

As discussed in Section 2.9, the design basis for RBC denitrification is not well established. Autotrol is the only manufacturer marketing RBC denitrification systems at this time (September, 1982). Their design procedure, developed primarily from RBC pilot studies conducted by Murphy et al. (31), assumes that in the presence of an adequate organic carbon source denitrification is independent of nitrate nitrogen concentration in the bulk liquid down to 1 mg/l. The zero-order denitrification rate determined by Murphy et al. with methanol addition is approximately 0.85 lb NO_3-N/day/1000 sq ft at 55°F.

Conversely, pilot-scale RBC data developed by Blanc et al. (32) also using methanol addition exhibit a first-order relationship between denitrification rate and bulk liquid nitrate nitrogen concentration in the range of 1 to 6 mg/l NO_3-N. As shown previously in Figure 2-14, their observed denitrification rates increased from about 0.08 lb NO_3-N/day/1000 sq ft at 1 mg/l to approximately 0.65 lb NO_3-N/day/1000 sq ft at 6 mg/l.

Denitrification rates reported for attached growth systems other than RBC's vary widely (33). For high-posity packed bed systems with various media types including Koch flexirings, intalox saddles, Raschig rings, and Surfpac plastic media, observed rates range from 0.026 to 0.24 lb NO_3-N/day/1000 sq ft at wastewater temperatures of 50 to 75°F. Higher rates have been reported for high-porosity fluidized bed systems including sand and activated carbon, varying from 0.66 to 9.8 lb NO_3-N/day/1000 sq ft at temperatures of 60 to 75°F. The zero-order design removal rate recommended by Autotrol (4) for RBC's of 0.92 lb NO_3-N/day/1000 sq ft at 55°F falls between the ranges reported for packed and fluidized bed column systems.

5.6.2 Design Curves

Autotrol has developed a series of RBC denitrification design curves for domestic wastewater relating hydraulic loading to influent and effluent nitrate nitrogen concentrations at 55°F (4). These curves are reproduced in Figure 5-23. As shown, the maximum influent concentration considered is 30 mg/l NO_3-N, while the minimum design effluent value for any condition is 1 mg/l NO_3-N. The mass removal rates represented by the eight curves are essentialy the same, i.e., 0.92 lb NO_3-N/day/1000 sq ft.

For wastewater temperatures other than 55°F, Autotrol recommends the application of an Arrhenius correction curve (Figure 5-24), also based on the work of Murphy et al. (31). Figure 5-24 was developed using a single four-stage, 19.7-in diameter RBC pilot unit at flows of 0.65 to 1.05 gpm and may require

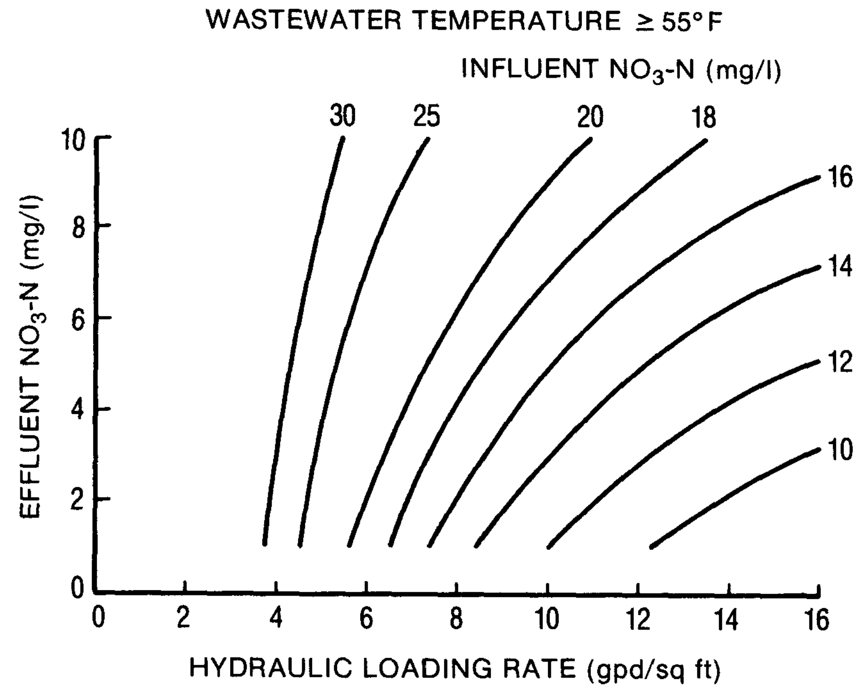


Figure 5-23. Autotrol denitrification design relationships [from Autotrol design manual (4)].

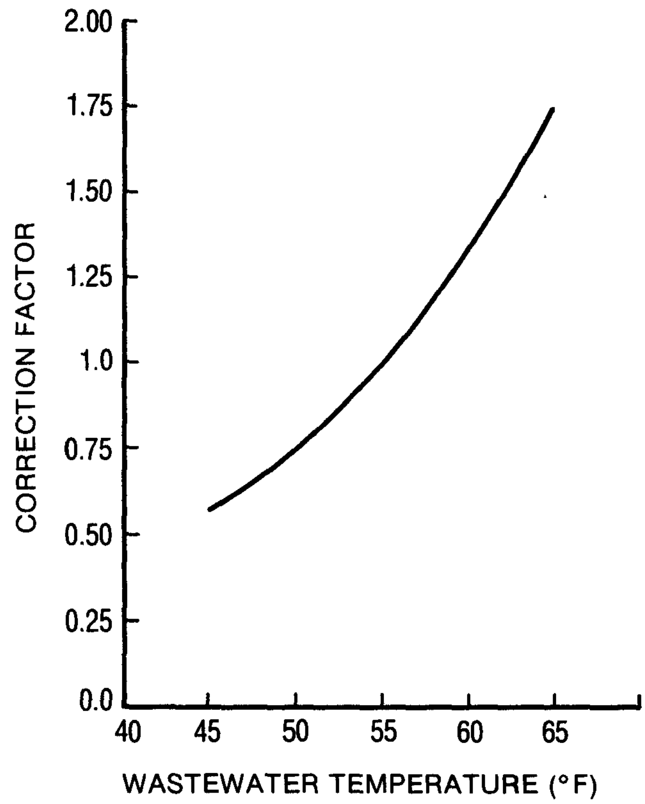


Figure 5-24. Autotrol temperature correction factors for denitrification [from Autotrol design manual (4)].

further adaptation when full-scale denitrification performance data become available.

5.6.3 Performance Data

No known full-scale municipal RBC denitrification systems had been in operation for a sufficient period when this document was completed (September 1982) to produce representative equilibrium data. One plant, the Orlando, Florida (Easterly) Iron Bridge Water Pollution Control Facility (34), was in its startup phase but had yet to establish routine operation.

An RBC system has been used to treat leachate from a garbage dump landfill at Miyazaki City, Japan, since 1977 (35). The leachate is characterized as low in BOD_5 (10 to 30 mg/l), moderate in suspended solids (30 to 100 mg/l), low in phosphorus (non-detected), and high in ammonia nitrogen (100 to 140 mg/l) with sufficient alkalinity (800 to 1100 mg/l) to support nitrification. Design influent concentrations were selected as 50, 100, and 200 mg/l, respectively, for BOD_5, suspended solids, and ammonia nitrogen with effluent objectives of 20 mg/l BOD_5, 25 mg/l suspended solids, and 50 mg/l NO_3-N.

A sequential RBC train with three separate functional RBC units was installed to treat the Miyazaki City leachate. The first unit consists of a conventional four-stage RBC reactor designed to reduce the incoming minimal BOD_5 load to a low residual level and oxidize the highly-concentrated ammonia nitrogen load to nitrate nitrogen. The second unit is a submerged four-stage RBC whose function is to denitrify the nitrate nitrogen produced in the first unit. Methanol is added to this unit. A final, short-detention (34-min), four-stage RBC unit oxidizes residual methanol and reaerates the final effluent. Clarification is provided only after the RBC reaeration unit.

Design flow and design wastewater temperature for this RBC system are 0.092 mgd and 59^{o}F, respectively. Phosphoric acid is added ahead of the first RBC unit to prevent phosphorus deficiency from developing within the biofilms. Based on metabolic consumption of 20 mg/l NH_3-N in the nitrification unit, the denitrification reactor was designed to handle 180 mg/l NO_3-N at an application rate of 1.51 lb/day/1000 sq ft. For an effluent requirement of 50 mg/l NO_3-N, the design removal rate is 1.09 lb NO_3-N/day/1000 sq ft. It is not known if the Autotrol denitrification design procedure for municipal systems was a major consideration in the selection of design criteria at Miyazaki City.

The Miyazaki City RBC facility was started up in the fall of 1976. Published performance data are available for 7 of the first 11 mo of 1977 (35). For these 7 mo, BOD_5 removal averaged 70 percent (20 mg/l in, 7 mg/l out), suspended solids removal 89 percent (45 mg/l in, 5 mg/l out), and total nitrogen removal 88 percent (129 mg/l NH_3-N in, 14 mg/l NH_3-N + NO_3-N out). Detailed performance data for the denitrification unit are presented in Table 5-8.

TABLE 5-8. RBC DENITRIFICATION PERFORMANCE AT MIYAZAKI CITY, JAPAN (1977)

Month	% of Design Flow	Wastewater Temp. (^{o}F)	NO_3-N In (mg/l)	NO_3-N Out (mg/l)	NO_3-N Rem. (%)	Loading Rate $\left(\frac{lb\ NO_3\text{-}N}{day \cdot 1000\ sq\ ft}\right)$	Pemoval Rate $\left(\frac{lb\ NO_3\text{-}N}{day \cdot 1000\ sq\ ft}\right)$
Jan.	21	48	102	15	85	0.18	0.15
Feb.	19	46	108	Tr	100	0.17	0.17
May	34	72	26	11	58	0.07	0.04
June	47	75	70	13	81	0.28	0.23
July	53	86	68	5	93	0.30	0.28
Aug.	43	86	67	14	79	0.24	0.19
Nov.	71	73	77	2	97	0.46	0.45
Avg.	41	69	74	9	85	0.24	0.21

Nitrate loading rates documented in Table 5-8 were not sufficiently high to stress the Miyazaki City denitrification reactor to its design removal capacity. The data do indicate that submerged biodiscs operating in the presence of an adequate organic carbon source can effectively reduce nitrate nitrogen to nitrogen gas. Substantiation of design criteria will require additional operating and performance results, particularly from plants with much lower nitrogen concentrations typical of municipal wastewater.

5.7 Design Case History for Combined Carbonaceous and Nutrient Removal

The Orlando Easterly plant is an advanced secondary treatment facility designed to achieve efficient removal of nitrogen and phosphorus as well as organics. Design flow is 24 mgd. The plant's liquid stream process units are shown schematically in Figure 5-25 (34). RBC's comprise the biological treatment components of the plant and are used for carbonaceous oxidation, nitrification, and denitrification. Mineral addition capability is provided at several feed points to precipitate phosphorus and improve solids capture. Effluent filtration assures low residual suspended solids in the plant discharge. Post aeration is utilized to raise effluent DO to permit levels.

Combined carbon oxidation-nitrification is accomplished in an air drive RBC reactor. Nineteen parallel trains of nine shafts each (171 total) are

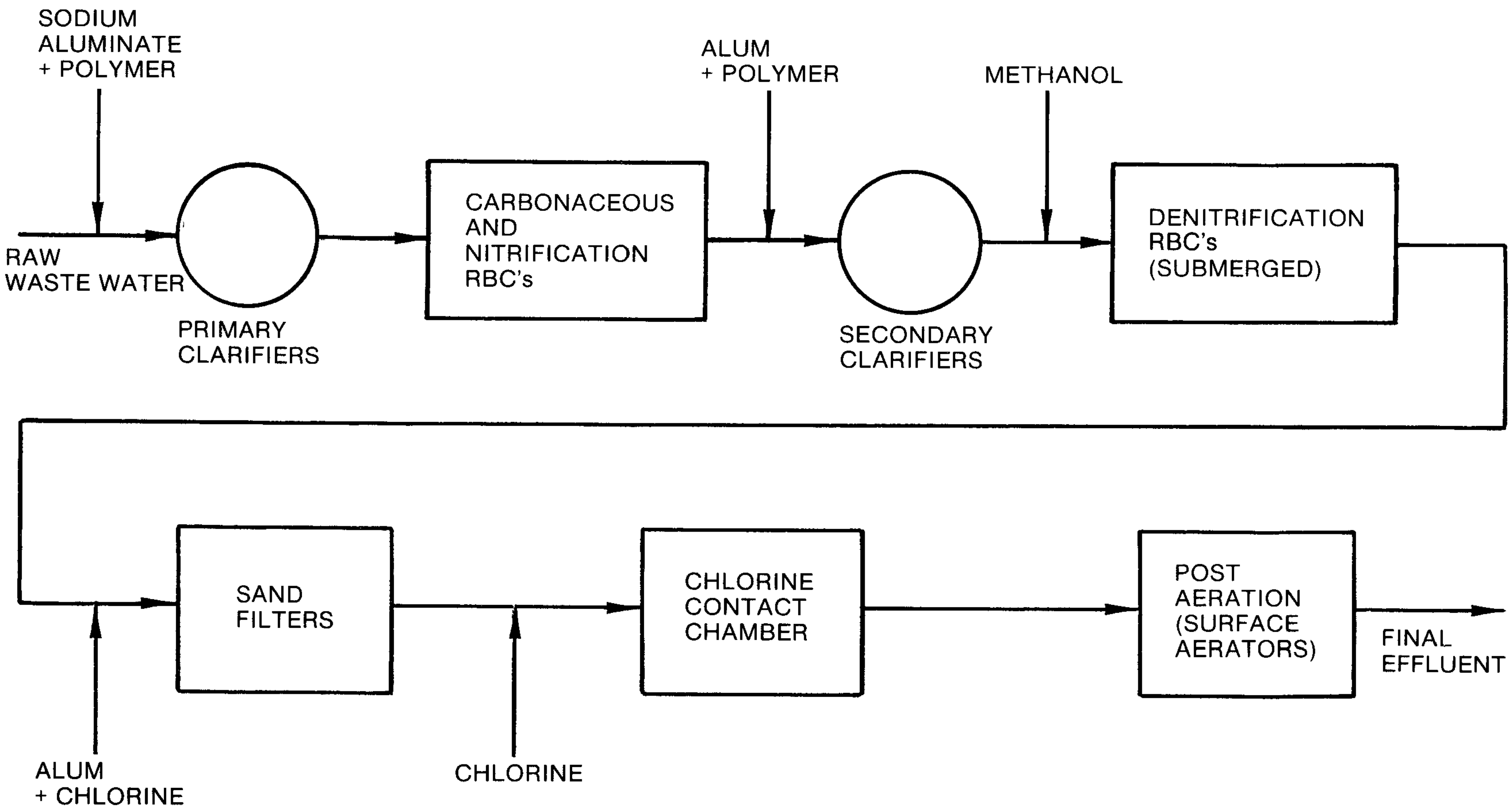


Figure 5-25. Process flow diagram for Orlando, Florida (Easterly) Iron Bridge Water Pollution Control Facility [adapted from Dallaire (34)].

provided for this purpose. The first three shafts in each train are equipped with standard density media (100,000 sq ft/shaft) and the last six with high density media (150,000 sq ft/shaft). The nine-shaft trains are divided into five stages using a 3-2-2-1-1 configuration. Primary efflent can be step feed to the first two stages.

The original design specified 180 mechanical drive units for carbonaceous oxidation and nitrification. A 5-percent reduction in required media surface area was achieved by the switch to air drive.

Each air drive shaft is outfitted with a load cell. An attempt will be made by the plant staff to distribute organic loading and air supply to limit biofilm thickness on the carbonaceous stages to 50 mils (0.05 in) (36). Each shaft is also equipped with an individual air throttling value. Two 400-hp, 16,000-cfm blowers, one operating, one standby, supply air to drive the carbonaceous and nitrification units. The media on the first four shafts of each train have 6-in. deep air cups, while the depth of the cups on the last five stages is 4 in.

Denitrification is achieved with 42 submerged, mechanically driven RBC's consisting of six trains of seven shafts each. An under-over-under baffle arrangement effectively divides each shaft into a separate stage. The shafts are rotated with 5-hp motors, although normal power draw is expected to be closer to 3 hp (36). The media surface area provided on each shaft is 108,000 sq ft. The denitrification media are rotated countercurrent to flow except for the last stage, which is rotated with flow to help lift sloughed solids over the last baffle weir.

Organic carbon necessary to expedite the anoxic denitrification reactions is supplied by methanol addition. Methanol dose is automatically controlled by feedback signals from a flow meter and an autoanalyzer that continuously monitors incoming nitrate nitrogen concentration.

The denitrification tanks are covered with 100-mm diameter, high density polyethylene, floating spheres formulated to include carbon black. These spheres cover approximately 92 percent of the tank surface and reduce atmospheric reaeration to 10 to 12 percent of that of an open tank. Nitrogen gas can escape to the atmosphere and rain can fall through openings between the spheres. Alternatives to the floating-sphere concept that were considered included floating plank styrofoam with nylon straps and neoprene membranes with rigid support frames (36).

An interesting feature of the Orlando Easterly physical layout is that the RBC trains (both aerobic and anoxic) are arranged in parallel rows of two. A gap has been provided between each set of rows extending the entire length of the trains to permit crane access for shaft removal, if necessary. With this configuration, the required crane reach is limited to one shaft length or approximately 30 ft and a 40- to 50-ton crane will suffice. If the required crane reach is extended to two shaft lengths, a 150-ton crane is necessary (36).

Roughing primaries, designed to achieve 30 to 50 percent suspended solids removal, were selected for Orlando Easterly. Wastewater temperatures always exceed the industry-established design temperature of 55°F, above which media surface area correction factors are not applied. Peak dry weather design flow is 30 mgd. Raw wastewater characteristics used as the basis of design and the plant's discharge permit requirements are summarized below (34)(37):

Parameter (mg/l)	Raw Wastewater	Discharge Permit Requirements
$TBOD_5$	230	5
$SBOD_5$	75	-
TSS	230	5
Total N	30	3
NO_3-N	Tr	1
Total P	8	1
DO	Nil	7

The plant's discharge permit requirements are very stringent and will require excellent process control on a day-to-day basis to meet standards. Using an average design flow of 24 mgd and based on a primary effluent soluble BOD_5 concentration of 75 mg/l, a primary effluent equivalent NH_3-N concentration of 24 mg/l, and a denitrification reactor influent NO_3-N concentration of 22 mg/l (37), the following process design loading rates can be calculated:

<u>Carbonaceous-Nitrification Reactor</u>

Hydraulic loading: 1.05 gpd/sq ft

Organic loading: 2.65 lb $SBOD_5$/day/1000 sq ft (first stage)
0.66 lb $SBOD_5$/day/1000 sq ft (overall)

Ammonia nitrogen loading: 0.28 lb NH_3-N/day/1000 sq ft (stages 2 to 5)
0.21 lb NH_3-N/day/1000 sq ft (overall)

<u>Denitrification Reactor</u>

Hydraulic Loading: 5.3 gpd/sq ft

Nitrate nitrogen loading: 0.97 lb NO_3-N/day/1000 sq ft

Secondary Clarifier

Hydraulic loading: 600 gpd/sq ft

At the time of this writing (September 1982), the Orlando Easterly plant was still undergoing startup and shakedown. No routine operating and performance data had yet been generated. Since it is the first-of-a-kind and because of its high performance expectations, progress at this advanced secondary facility will be followed closely by the municipal wastewater treatment field.

5.8 General Plant Design Considerations

Proper design of an RBC installation entails, among other things, an adequate determination of influent and sidestream loadings and the selection of an overall plant layout that ensures the RBC system is compatible with the other unit processes selected. In addition, RBC system design should provide sufficient flexibility to promote good operation and maintenance practices. In this regard, there are a number of design considerations germane to RBC installations that should be addressed.

In general, housing RBC units within a building (as opposed to using individual covers for the RBC units) is undesirable because of the corrosive atmospheric conditions associated with H_2S release and the high humidities that result. Condensation problems have been encountered on interior building walls in cold climates, and the associated high humidities and ventilation requirements increase heating costs. Where buildings are chosen, the building design must provide for removal of a shaft/media assembly should repair or replacement prove necessary. In contrast to individual fiberglass covers, full building cover normally provides more convenient access to RBC's for routine maintenance and visual observation.

In all RBC designs, access to individual shafts for repair or possible removal must be considered. Bearings should also be accessible for easy removal and replacement if necessary. The weight of a 27-ft long shaft and media assembly may be expected to range from 18,000 to 25,000 lb for clean media depending on whether standard or high density media is specified. A fully loaded 100,000-sq ft shaft with a 0.1-in. thick biofilm has a dead weight of about 70,000 lb. Some manufacturers assemble their units in such a way that the media can be removed from the shaft while the shaft remains in the RBC tank (Clow, Crane-Cochrane, and Lyco), whereas the media of another manufacturer (Autotrol) can only be removed nondestructively once the shaft has been lifted from the tank. The Walker Process media is epoxy bonded to the shaft. Where all units in a large installation are physically located very close together, it has been necessary to utilize large off-the-road cranes for shaft removal. Crane reach, crane size, and the impact of being able to drain RBC tankage and dry a unit prior to shaft removal should all be considered when designing the RBC layout.

Whenever multiple process trains are employed, provision for positive and measureable flow control to individual trains is essential. Use of single, long influent channels with slide gate control for individual trains makes it difficult for the operator to locate flow maldistributions and implement appropriate corrective procedures. Splitter boxes and/or weirs are low cost solutions to this problem. Provision of adequate flow control equipment is especially important if individual trains are fed from a single channel with rotation of some trains with and other trains against the direction of plant flow.

Feeding and discharge flexibility should be considered in RBC design. Step feed capability can relieve overloaded first stage(s) and potentially decrease or eliminate excessively thick biofilm growth. Removable baffles may also be effective in this regard. In underloaded plants, the final stages frequently must be operated to keep suspended solids in suspension rather than to provide additional treatment to meet effluent standards; capability to temporarily bypass these terminal units would result in energy and operation and maintenance savings. If sufficient flow flexibility is available, loss of an individual unit need not result in shutting down an entire process train. Adjustment of total flow/loading distribution may be an operational necessity, again emphasizing the need for positive and measurable flow control and/or splitting.

Load cells, especially in the first stage(s), can provide useful operating and shaft load data. Where parallel trains are in operation, they can pinpoint overloaded or underloaded trains. Stop motion detectors, rpm indicators, and clamp-on ammeters are also potentially useful monitoring instruments.

The use of deep channels leading to and exiting from RBC tanks has resulted in solids deposition and subsequent accumulation at a number of installations. Providing for channel aeration (3.5 scfm/linear foot) or employing channel configurations that promote adequate scouring velocity should overcome this problem.

Most RBC designs are based on the units operating at a submergence of approximately 40 percent based on total media surface area. To avoid possible shaft overstressing and inadequate media wetting, the RBC manufacturers strongly recommend never dropping the liquid operating level below 35-percent submergence. They also recommend a clearance of 4 to 9 in. between the tank floor and the bottom of the rotating media to maintain sufficient bottom velocities to prevent solids deposition in the tank.

Depending on media formulation, e.g., the use of carbon black, media strength can be severely degraded by exposure to sunlight (ultraviolet degradation). When RBC units are stored on-site for an extended period of time prior to installation, provisions must be made to ensure that they remain protected from direct sunlight. Media can also be severely impacted by high wastewater temperatures (>95°F); this is a potential problem in some industrial applications or in municipal installations that receive large industrial flows or are located in desert-like environments.

Equipment warranties can be negotiated with the manufacturers, and, in some cases, extended equipment warranties have been obtained. This possibility should be thoroughly considered in equipment specifications. Although RBC manufacturers continue to make improvements in their equipment, major equipment problems and failures have occurred at some installations.

The impact of sidestreams from other unit processes on RBC performance must be considered. Anaerobic digesters increase ammonia nitrogen loadings, and sludge conditioning processes such as heat treatment contribute increased organic and ammonia nitrogen loadings. Whenever septic tank discharges comprise part of the influent wastewater or any unit processes are employed that may produce sulfide ahead of the RBC units, the additional oxygen demand associated with sulfide must be considered in system design. High influent grease loads require the use of primary clarifiers instead of screens.

Most existing air drive installations do not have provisions for measuring and controlling air flow to individual RBC units. Furthermore, in some plants (see Figures 4-3 and 4-4), the possibility that some of the air drive diffusers have plugged cannot be easily verified. Operating an air drive facility under these types of "blind" conditions adds to the difficulty of appropriately responding to operational problems that may arise. The question of how much plant blower capacity should be provided is open to debate. A critical need exists for more information on the normal range of air flows that should be expected with air driven units.

5.9 References

1. Fair, G. M., J. C. Geyer, and D. A. Okun. Water Purification and Wastewater Treatment and Disposal. Vol. 2, p. 25-13, John Wiley and Sons, New York City, 1968.

2. Clark, J. H., E. M. Moseng, and T. Asano. Performance of a Rotating Biological Contactor Under Varying Flow. Journal WPCF, 50(5):896-911, May 1978.

3. Roy F. Weston, Inc. RBC DIS Subtask on RBC Design Approaches. Internal report prepared for USEPA under Contract No. 68-03-3019, Cincinnati, Ohio, March 5, 1982.

4. Autotrol Wastewater Treatment Systems Design Manual. Autotrol Corporation, Bio-Systems Division, Milwaukee, Wisconsin, 1978.

5. Clow Envirodisc Rotating Biological Contactor Systems Catalog. Clow Corporation, Florence, Kentucky, 1980.

6. RBC systems brochure for Manufacturer X, 1978.

7. Lyco Wastewater Products - RBS Systems Catalog. Lyco Division of Remsco Associates, Marlboro, New Jersey, 1982.

8. DuPont, R. R. and R. E. McKinney. Data Evaluation of a Municipal RBC Installation, Kirksville, Missouri. In: Proceedings of the 1st National Symposium/Workshop on Rotating Biological Contactor Technology, Vol. I, EPA-600/9-80-046a, NTIS PB81-124539, June 1980. pp. 205-234.

9. Srinivasaragharan, R., C. W. Reh, and S. Liljegren. Performance Evaluation of Air Driven RBC Process for Municipal Waste Treatment. Ibid. pp. 525-552.

10. Orwin, L. W. and C. D. Siebenthal. Hydraulic and Organic Forcing of a Pilot-Scale RBC Unit. Ibid. pp. 119-136.

11. Stover, E. L. and D. F. Kincannon. Evaluating Rotating Biological Contactor Performance. Water and Sewage Works, 123(3):88-91, March 1976.

12. Murphy, K. L. and R. W. Wilson. Pilot Plant Studies of Rotating Biological Contactors Treating Municipal Wastewater. Report SCAT-2, Environment Canada, Ottawa, Ontario, Prepared for Canada Mortgage and Housing Corporation, July 1980.

13. Chou, C. C., R. J. Hynek, and R. A. Sullivan. Comparison of Full Scale RBC Performance with Design Criteria. Bio-Surf Process Technology Book, Autotrol Corporation, Milwaukee, Wisconsin, (No date).

14. Existing Plant Summaries. Bio-Surf Process Technology Book, Autotrol Corporation, Milwaukee, Wisconsin, (No date).

15. Personal communication from R. A. Sullivan, Autotrol Corporation, Milwaukee, Wisconsin, to J. A. Heidman, USEPA, Cincinnati, Ohio, January 13, 1982.

16. Srinivasaraghavan, R., C. W. Reh, and J. Canady. Plant Scale Investigation of RBC Process Supplemental Aeration. In: Proceedings of the 1st National Symposium/Workshop on Rotating Biological Contactor Technology, Vol. I, EPA-600/9-80-046a, NTIS PB81-124539, June 1980. pp. 575-598.

17. Opatken, E. J. Rotating Biological Contactors - Second Order Kinetics. In: Proceedings of the First International Conference on Fixed-Film Biological Processes, Vol. I, EPA-600/9-82-023a, Kings Island, Ohio, April 20-23, 1982. pp. 210-232.

18. Friedman, A. A., R. C. Woods, and R. C. Wilkey. Kinetic Response of Rotating Biological Contactors. In: Proceedings of the 31st Industrial Waste Conference Purdue University, West Lafayette, Indiana, May 4-6, 1976; Ann Arbor Science, Ann Arbor, Michigan, 1977. pp. 420-433.

19. Hynek, R. J. and C. C. Chou. Development and Performance of Air-Driven Rotating Biological Contactors. In: Proceedings of the 34th Industrial Waste Conference, Purdue University, West Lafayette, Indiana, May 8-10, 1979; Ann Arbor Science, Ann Arbor, Michigan, 1980. pp. 805-815.

20. Levenspiel, O. Chemical Reaction Engineering. John Wiley and Sons, New York City, 1972.

21. Letter (data) communication from J. Iannone, Roy F. Weston, Inc., Roslyn, New York, to E. J. Optaken, USEPA, Cincinnati, Ohio, December 7, 1981.

22. Borchardt, J. A., S. J. Kang, and T. H. Chung. Nitrification of Secondary Municipal Waste Effluents by Rotating Bio-Discs. EPA-600/2-78-061, NTIS PB-285 240/8BE, June 1978.

23. Antonie, R. L. Nitrification of Activated Sludge Effluent with the Bio-Surf Process. Presented at the Annual Conference of the Ohio Water Pollution Control Association, Toledo, Ohio, June 7-13, 1974.

24. Crawford, P. M. Use of Rotating Biological Contactors for Nitrification at the City of Guelph Water Pollution Control Plant, Guelph, Ontario, Canada. In: Proceedings of the 1st National Symposium/Workshop on Rotating Biological Contactor Technology, Vol. II, EPA-600/9-80-046b, NTIS PB81-124547, June 1980. pp. 1247-1273.

25. Antonie, R. L. Nitrogen Control with the Rotating Biological Contactor. Autotrol Corporation brochure, Milwaukee, Wisconsin, (No date).

26. Pano, A., E. J. Middlebrooks, and J. H. Reynolds. The Kinetics of Rotating Biological Contactors Treating Domestic Wastewater. Water Quality Series UWRL/Q-81/04, Utah State University, College of Engineering, Logan, Utah, September 1981.

27. Letter (data) communication from R. A. Sullivan, Autotrol Corporation, Milwaukee, Wisconsin, to R. C. Brenner, USEPA, Cincinnati, Ohio, March 12, 1982.

28. Letter (data) communication from R. J. Hynek, Autotrol Corporation, Milwaukee, Wisconsin, to E. J. Opatken, USEPA, Cincinnati, Ohio, July 22, 1980.

29. Advanced Wastewater Pilot Plant Treatment Studies. Report prepared for City of Indianapolis by Reid, Quebe, Allison, Wilcox, and Associates, Inc., Indianapolis, Indiana, January 1975.

30. Letter (data) communication from W. L. Morley, Wastewater Treatment Plant, Gladstone, Michigan, to R. C. Brenner, USEPA, Cincinnati, Ohio, November 17, 1981.

31. Murphy, K. L., P. M. Sutton, R. W. Wilson, and B. E. Jank. Nitrogen Control: Design Considerations for Supported Growth Systems. Journal WPCF, 49(4):549-557, April 1977.

32. Blanc, F. C., J. C. O'Shaughnessy, D. J. Connick, and D. Wood. Denitrification of Nitrified Municipal Wastewater Using Rotating Biological Contactors. In: Proceedings of the 1st National Symposium/Workshop on Rotating Biological Contactor Technology, Vol. II, EPA-600/9-80-046b, NTIS PB81-124547, June 1980. pp. 1275-1300.

33. Process Design Manual for Nitrogen Control. EPA-625/1-75-007, USEPA, Center for Environmental Research, Cincinnati, Ohio, October 1975.

34. Dallaire, G. U.S.'s Largest Rotating Biological Contactor Plant to Slash Energy Use 30%. Civil Engineering, ASCE, 49(1):70-72, January 1979.

35. Hynek, R. J. and H. Iemura. Nitrogen and Phosphorus Removal with Rotating Biological Contactors. In: Proceedings of the 1st National Symposium/Workshop on Rotating Biological Contactor Technology, Vol. I, EPA-600/9-80-046a, NTIS PB81-124539, June 1980. pp. 295-324.

36. Personal communications from D. W. Bouck, Dawkins and Associates, Inc., Orlando, Florida, to R. C. Brenner, USEPA, Cincinnati, Ohio, November 16, 1981.

37. Personal communication from R. J. Hynek, Autotrol Corporation, Milwaukee, Wisconsin, to R. C. Brenner, USEPA, Cincinnati, Ohio, September 20, 1982.

☆ U S GOVERNMENT PRINTING OFFICE 1984- 759-102/0973