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Summary of Design Information on Rotating Biological Contactors

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SUMMARY OF DESIGN INFORMATION ON ROTATING BIOLOGICAL CONTACTORS

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EPA REVIEW NOTICE

FOREWORD

Rotating biological contactors (RBCs) are relatively new to secondary wastewater treatment in the United States, with over 500 municipal facilities being installed in the last decade. In addition to secondary treatment applications, RBCs have also been used successfully to upgrade marginal treatment facilities and to provide nitrification. Because of a variety of problems related to the design, construction, operation, and application of RBC facilities throughout the country, the U.S. Environmental Protection Agency has undertaken a number of research projects to investigate and identify the nature and extent of these problems and to determine possible solutions. These efforts have indicated that when properly designed, built, and operated, RBCs can provide an acceptable alternative to conventional activated sludge systems.

The Wastewater Research Division of the Municipal Environmental Research Laboratory, located in Cincinnati, Ohio, has conducted a comprehensive array of research projects on various aspects of the RBC treatment process, including the theoretical basis of the process, process design and operational considerations, and equipment reliability and design. The results and findings of these projects are detailed in a Municipal Environmental Research Laboratory publication entitled "Design Information on Rotating Biological Contactors" (EPA-600/2-84-106). This publication is available from the National Technical Information Service (NTIS PB84-199561).

This Summary document is extracted from the above publication and presents in a concise form essential information on the design, construction, operation, and application of the RBC process. It is intended to provide a basic understanding of the process and its application for the treatment of municipal wastewaters, and will be of use to design engineers, governmental agency review personnel, municipal officials, operators, and others with an interest in the RBC process.

CONTENTS

SECTION 1

INTRODUCTION

The relatively rapid introduction of rotating biological contactors (RBCs) into the United States for municipal and industrial wastewater treat ment 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 empirical design procedures generated by various manufacturers. More recently, as interest in the process has increased, alternative design approaches have begun to appear in the technical literature.

This document highlights design information and supplements commonly accepted RBC design methodology, such as manufacturers' design manuals and empirical and deterministic models found in the literature, by providing additional information and summaries of operating and performance data not readily available to the design community. Most of the data used in evaluating the RBC process were obtained from the technical literature, conference proceedings, and the files of the manufacturers. Important design parameters and relationships (or lack of them) are discussed to promote a more rational RBC design approach.

The purpose of this document is to concisely summarize RBC design information for municipal wastewater currently available in a number of EPA publications (1)(2)(3)(4). When a more in-depth discussion of a particular topic is desired, the reader may wish to consult the original publications for further details. Topics addressed include process and equipment descriptions, equipment reliability, organic removal, nitrification, and energy requirements. A major priority was given to emphasizing practical, usable design information as well as important theoretical concepts. This summary is not intended to serve as a "cook book" design reference or to replace other available design guides from either manufacturers or the technical literature.

SECTION 2

PROCESS DESCRIPTION

All RBC systems are cylindrical-type structures consisting of plastic media attached to and/or supported by horizontal rotating shafts. The first commercial RBC system was installed in West Germany in 1960. Units constructed from this time to the early 1970s used flat 0.5-in. thick, 6.5- to 10-ft diameter expanded polystyrene discs. All present systems use thin (0.04 to 0.06 in.), high density plastic media either formed as discs or sections of discs and aligned perpendicular to the shaft, or spirally wound onto and aligned parallel to the shaft. The media configuration, method of media attachment to the shaft, available surface area per unit shaft length, method of rotating the shaft, etc., vary with each manufacturer. An in-depth discussion of available equipment is presented in Section 3.

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 organics removal and nitrification, and 5 percent for nitrification of secondary effluent (5). When used for these applications, the RBC shafts are positioned over the wastewater surface such that about 40 percent of the media is submerged at any time. The shafts are rotated slowly (1 to 2 rpm) causing an alternating exposure of the media to the atmosphere and the wastewater. Biological growth (biofilm) becomes attached to the surface of the media and forms a slime layer over the entire surface of the discs. The biological population that develops on each unit reflects the environmental and loading conditions unique to each shaft, and simple visual observation reveals a gradation in slime thickness and color in staged systems. The first stage in a system operating within the proper organic loading range exhibits a characteristic brownish-grey color, while terminal stages that are nitrifying normally have a characteristic reddish-bronze color (6). The rotation of the discs alternately contacts the biofilm with organic material in the wastewater and then with the air. Shearing forces exerted on the biofilm as it passes through the wastewater cause excess biological growth to be sloughed off the media into the stage liquor where the turbulence created by disc rotation maintains the sloughed biomass in suspension.

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. These considerations are addressed in more detail in Section 5.

A typical RBC application for secondary treatment is depicted in Figure 1. Here, flow passes from the primary clarifier through the series arrangement of RBC units and then to a final clarifier where the excess biofilm sheared from the RBC unit is settled. In some installations, screens are used in place of primary clarifiers with a resultant increased solids and biochemical oxygen demand (BOD) load to the RBC system. If the RBC unit was receiving a secondary effluent and was designed to provide nitrification, a clarifier following nitrification would not necessarily be required.

When the dissolved oxygen (DO) level is at or near zero, many heterotrophic microorganisms are able to reduce nitrate nitrogen to nitrogen gas. This phenomenon is used in wastewater treatment systems for nitrogen removal (denitrification). Unoxidized nitrogen must first be converted to nitrate nitrogen in an aerobic environment. Denitrification can then 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. RBC systems can also be staged with the anoxic unit as the first stage of the RBC with the organic carbon naturally present in the incoming wastewater used for nitrate reduction. Nitrate nitrogen must be introduced to this stage by recirculation of nitrified wastewater from the downstream stages.

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 (7). Only one full-scale, municipal RBC denitritrification facility was in operation in the United States (8) as of August 1984.

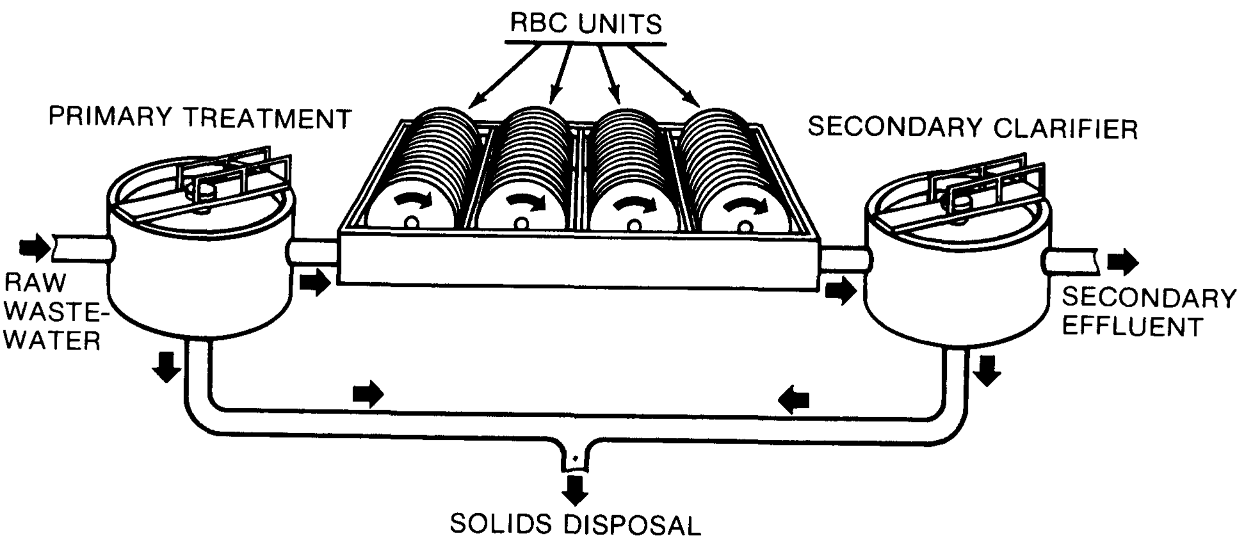


Figure 1. Typical RBC plant schematic for secondary treatment application [from Autotrol design manual (7)].

SECTION 3

EQUIPMENT DESCRIPTION

INTRODUCTION

The five major U.S. manufacturers marketing RBC equipment at the present time are Clow, Crane-Cochrane, Envirex (formerly Autotrol), Lyco, and Walker Process. Each manufacturer designs the RBC with an individuality that is unique to its firm. Consequently, RBCs 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 among 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.

SHAFTS

RBC shafts are used to support and rotate the plastic media. Maximum shaft length is presently limited to approximately 27 ft, with 25 ft occupied by media. Shorter shaft lengths are also available. The shafts are fabricated from steel and are covered with a protective coating suitable for water and high humidity service. Proper protective coating procedure requires sand blasting of the steel prior to the coating application. A coal tar epoxy is normally used as the protective coating with a minimum film thickness of 14 mils (0.014 in.).

Each manufacturer designs its own shape, size, and thickness of shaft. The wall thickness of the shaft 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 shown in Figure 2 and identified in Table 1. Lyco currently manufactures Series 300 circular shafts. The previous Lyco/Hormel Series 200 octagonal shaft is also included in Table 1 because of the large number of installations still using it.

MEDIA

The heart of the RBC process is the plastic media. In 1972, the high density polyethylene (HDPE) disc was introduced as a cost reduction alternative to the previously used 0.5-in. thick polystyrene disc. The major

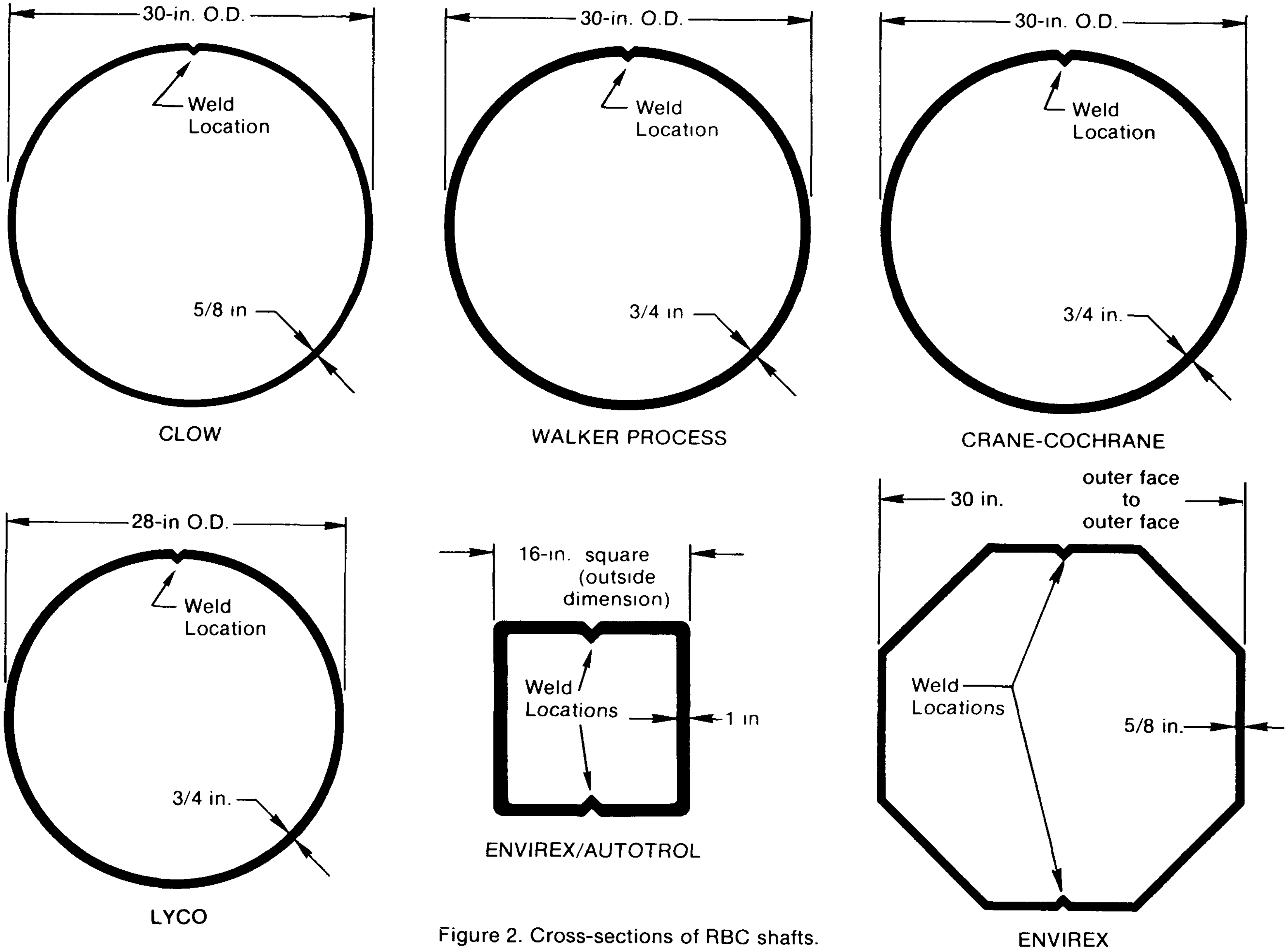


Figure 2. Cross-sections of RBC shafts.

TABLE 1. SHAFT CHARACTERISTICS

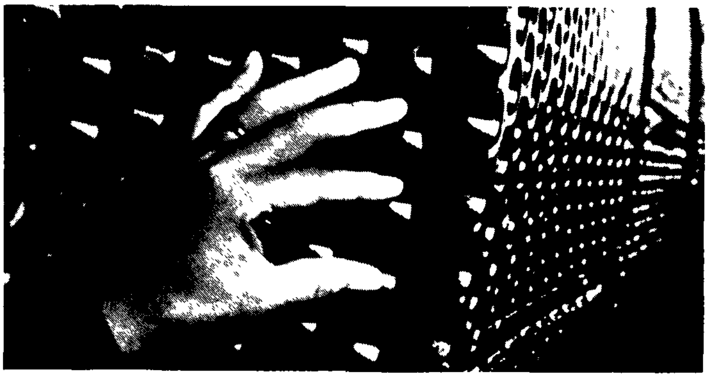
Manufacturer	Shape	Size (in.)	Thickness (in.)	Section Modulus ($in.^3$)	Ref.
Clow	Round	30	0.625	415	9
Crane-Cochrane	Round	30	0.75	492	10
Envirex	Octagonal	30	0.625	434	11
Envirex/Autotrol	Square	16 x 16	1.00	282	7
Lyco	Round	28	0.75	426	12
Lyco/Hormel	Octagonal	24	0.75	344	12
Walker Process	Round	30	0.75	492	13

advantage of polyethylene is its ability to be formed into various configurations 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 a 27-ft shaft with 12-ft diameter media. Today, all U.S. manufacturers of RBCs utilize polyethylene as their plastic media.

Various media configurations or corrugation patterns have been selected by the manufacturers, each with its own claimed advantages. Several examples are shown in Figure 3. There are several reasons for using corrugations. Corrugations add stiffness to the sheets and enable these sheets to be formed with diameters as large as 12 ft. Corrugations increase the available surface area by 15 to 20 percent. Corrugations 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. Finally, corrugations are used as spacers to keep the sheets separated.

Standard density media are normally used in the lead 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 shaft in which the media diameter is approximately 12 ft. By reducing the space required for the repeating plastic corrugations by 33 percent, the available surface area can be effectively increased by 50 percent; this results in shafts with 150,000 sq ft of media, commonly called 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.

RBC manufacturers employ various methods for supporting plastic media from their shafts. Clow, Crane-Cochrane, and Lyco rely on a coated steel or stainless steel radial arm system to support the plastic media. Envirex



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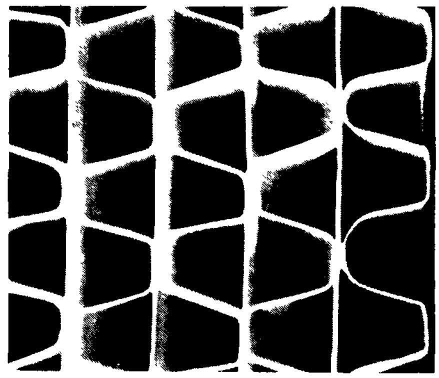
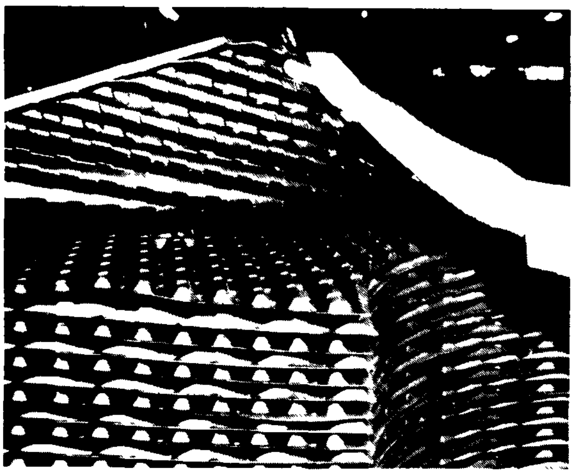
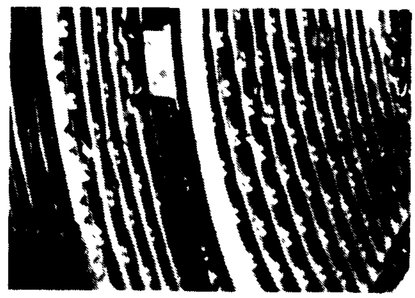


FROM AUTOTROL DESIGN MANUAL (7)



COURTESY OF CRANE-COCHRANE



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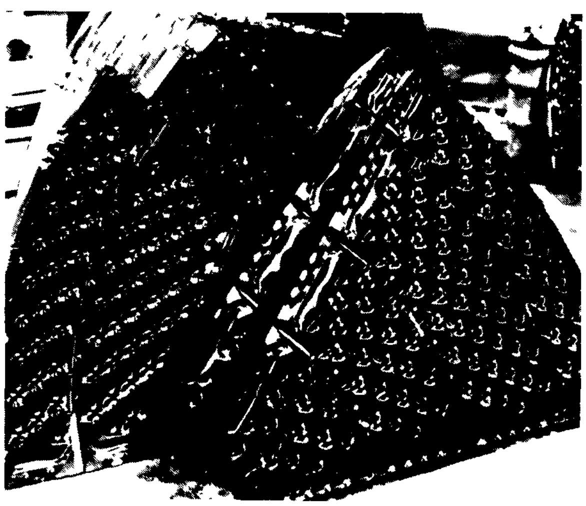

COURTESY OF CLOW

Figure 3. RBC media configurations.

employs plastic media hubs that fit onto its square and octagonal shafts with the plastic media sheets thermally welded to the hubs. Walker Process attaches the plastic media to the shaft with an epoxy bonding agent and stainless steel strips with the media then spirally wound onto the shaft in 35-in. wide strips.

DRIVE SYSTEMS

Historically, RBCs have been driven mechanically and the drive assembly has proven to be a very reliable equipment component. 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. The electric motors presently used for mechanical drive RBCs are normally high efficiency, 3-phase, 60-hertz units. The motors, designed with protective coatings for high humidity environments, are capable of providing long-term, reliable service. Energy requirements for mechanical drive systems are discussed in Section 7.

If the designer desires, the manufacturers can modify their standard drive packages to include variable speed capability. This provides the operator with additional flexibility for DO and biofilm thickness control. Methods for achieving variable speed capability include positive infinitely variable (P.I.V.) speed changers and variable frequency controllers, among others. P.I.V. speed changers are hand-adjusted units and work on the principle 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.

Envirex offers an air driven RBC unit. The air drive assembly consists of 4- or 6-in. deep plastic cups welded around the outer perimeter of the media and an air header placed below the media (Figure 4). 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. Air flow requirements are discussed in Section 7.

BEARINGS

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 corrosion by the use of moisture resistant bearings and cover plates on the idle end of the shaft has minimized another potential problem. To permit easy access for lubrication and maintenance, the bearings should be located outside the media covers.

LOAD CELLS

Hydraulic load cells are available and in use for periodically measuring total shaft weight. The shaft weighing device consists of a load cell bearing

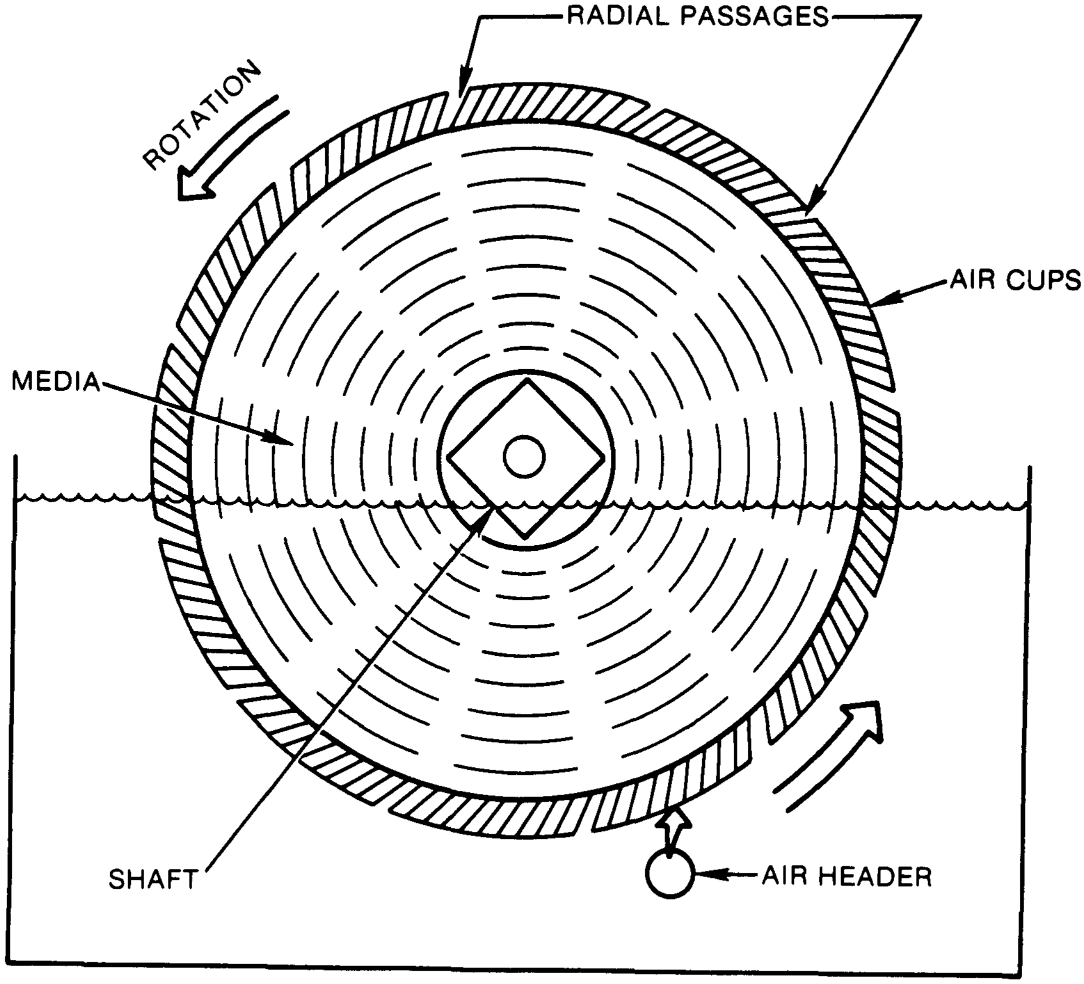

Figure 4. Air drive RBC schematic [from Autotrol design manual (7)].

installed on the idle end of a mechanically driven 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. The resulting hydraulic pressure is read from a gauge and the reading converted to shaft weight, which in turn can be used to estimate biofilm thickness. Such measurements are useful in determining conditions that may cause excessive fatigue stress on the shaft and increased energy consumption.

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 converter unit is available that when plugged into this type of load cell provides a direct readout of total shaft weight. 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.

COVERS

RBC systems not housed in buildings are normally protected from the elements by manufacturer-supplied covers. These covers are made of fiberglass or other reinforced resin plastics for durability and lightweight handling. They all conform to the general shape of RBC media and permit sufficient access to the units for observation and minor repairs. Most are designed in sections that can be readily dismantled when major repairs or shaft removal is required.

RBC ARRANGEMENT

Staging of RBC media is recommended to maximize removal of BOD and ammonia nitrogen (NH_3-N). In secondary treatment applications, three or four stages are generally provided for each flow stream. Additional stages may be added for nitrification or for combined BOD and NH_3-N removals. For small installations, four stages can be provided on a single shaft by installing three interstage baffles within the tank and introducing the flow parallel to the shaft. Installations requiring two RBC units may be placed in series with a single baffle in each tank, thus providing four stages. Four or more units can be placed in series, with each unit becoming a single stage. Various schemes of staging RBC units are shown in Figure 5.

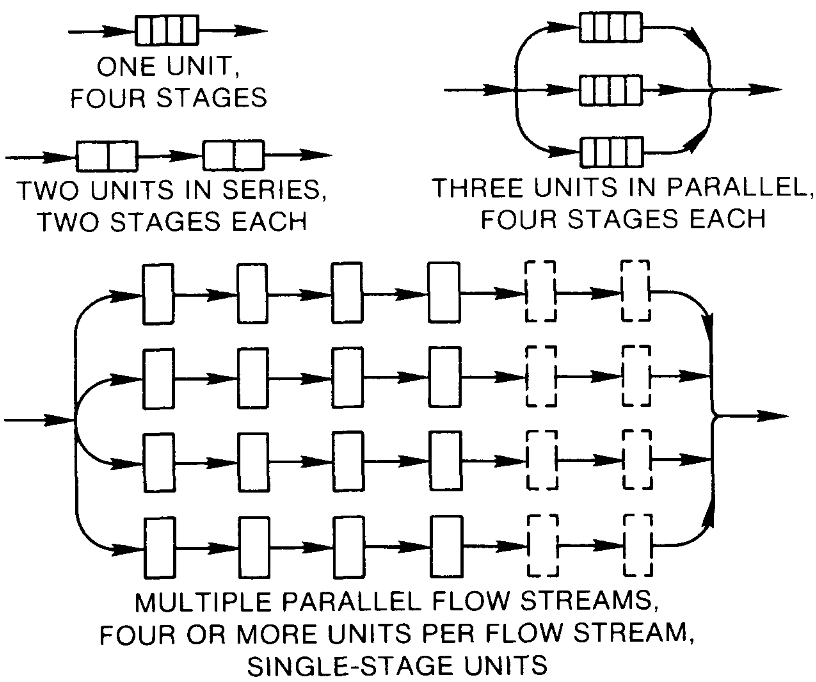

Figure 5. Various schemes of staging RBC units.

SECTION 4

EQUIPMENT RELIABILITY

INTRODUCTION

An EPA-sponsored study (3) of RBC facilities was conducted during the period of September 1979 through September 1982. On-site visits and telephone interviews were utilized to collect pertinent operation and maintenance (O&M) and equipment-related data from 16 plants equipped with polyethylene media. A partially updated summary of shaft and shaft-related failures from these 16 plants is presented in Table 2. For the 153 units included in this evaluation, 41 broken shafts, seven media attachment failures, and 16 bearing failures were reported.

SHAFTS

The most serious equipment problem that can impact an RBC plant is a shaft failure. 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 removal of protective media covers or relocation of the entire shaft assembly outside a process building.

The vast majority of shaft failures can be attributed to known design and manufacturing defects that have been addressed in the newer generations of shafts currently being marketed. In particular, use of a discontinuous backing strip during the welding of two 16-in. pieces of channel resulted in a number of defective shafts being fabricated that subsequently failed. Additional failures were also experienced from structural overloading of shafts that were designed with inadequate section modulus.

The wide variation in shaft design procedures has aroused considerable concern as to the adequacy of RBC shafts to provide 20 yr of reliable service. Assuming satisfactory welding practice, the most likely cause of shaft failure is fatigue. Extensive experimental testing of structural members with applied cyclic loads has shown that the logarithm of fatigue life is linearly related to the logarithm of the range of applied stress between certain limits of the cyclic life. The stress range at which this curve becomes flat is known as the fatigue limit and represents the theoretical value of the applied stress range for which no appreciable fatigue damage occurs under atmospheric conditions. A member subjected to rotating/cyclical loads with a maximum corresponding stress range less than the fatigue limit will not fail (within a certain high level of confidence). The standards of

TABLE 2. SUMMARY OF SHAFT AND SHAFT-RELATED FAILURES

Plant	No. of Shafts	RBC System Startup Year	Broken Shafts	Bearing Failures	Media Support Failures	Corrective Action Taken
Cheboygan, Mich.	8	1978	3	0	0	Replaced 3 shafts
Cleves, Ohio[a]	6	1977	0	0	0	
Edgewater, N.J.	4	1973	0	1	0	Replaced bearing
Gladstone, Mich.	6	1974	1	0	0	Welded in place
Gloucester, N.J.	4	1974	1	2	0	Replaced 2 bearings; replaced 4 shafts
Hamilton Township, N.J.	48	1979	6	0	0	Replaced 1 shaft[b]
Hartford, Mich.	2	1978	0	0	0	
Ionia, Mich.	12	1978	12	0	0	Replaced 12 shafts
North Huntington, Pa.	4	1975	3	2	0	Replaced all 4 shafts; replaced 2 bearings
Rhinelander, Wisc.	10	1977	6	0	0	Replaced all 10 shafts[c]
Selden, N.Y.	12	1974	0	8	0	Replaced 8 bearings
Thermopolis, Wyo.	2	1978	0	0	0	Replaced 2 shafts[d]
Voorhees Township, N.J.	6	1976	3	0	0	Replaced 6 shafts
Wappingers Falls, N.Y.	2	1978	0	1	4	Replaced bearing; replaced radial arms
Washington Township, N.J.	3	1974	0	0	3	Replaced radial arms
Winchester, Ky.	24	1977[e]	6[f]	2	0	Replaced 2 bearings

[a] Air driven RBC units.
[b] One shaft replaced as of August 1984. Replacement of the 5 remaining broken shafts is underway with completion projected by November 1984.
[c] All 10 shafts replaced due to anticipated failure of the remaining 4 units.
[d] Anticipated failure based on performance of similar units elsewhere.
[e] Plant upgraded from 4 to 24 shafts in 1980.
[f] Replacement of broken shafts under litigation.

the American Welding Society (AWS) include stress curves for structural members in several categories (14).

Geometry, detailing, and fabrication quality can each have a significant effect on the fatigue resistance of a member. Transverse or longitudinal welding, welded attachments, bolting, and weld toe treatment are factors that influence fatigue behavior. The weldment fabrication procedures of the AWS Structural Welding Code (14) should be adopted as the absolute minimum requirements. Fatigue resistance can also be affected by potential shaft corrosion due to the expected operating environment.

The estimated fatigue lives for a number of shaft configurations, media densities, and biofilm thicknesses were developed by Bowman and Gaunt (15). Current manufacturers' shaft designs used in conjunction with standard density media were projected to be resistant to failure from fatigue at biofilm thicknesses ranging from at least 75 mils (0.075 in.) to 150 mils (0.15 in.) or greater with the range reflecting the different shaft configurations employed by the various manufacturers. Further details are summarized elsewhere (1).

MEDIA

Six of the 16 plants visited in the aforementioned survey (3) reported problems with the media component, including hub failures, shifting media, media brittleness, and media breakage from unspecified causes. Failures can occur due to degradation of the polyethylene media from exposure to heat and/or concentrated organic solvents, or to UV degradation if anti-oxidants are not added to the media formulations. Failures have also occurred because of poor hub design, poor media welding procedures, and inadequately designed radial arm systems.

The method of forming a media pack and attaching that pack to the shaft determines whether an RBC assembly must be removed from its tank for field replacement of damaged media. Present media pack attachment designs of Clow, Crane-Cochrane, and Lyco do not require shaft removal to effect media replacement. Envirex and Walker Process designs require shaft removal.

DRIVE SYSTEMS

Some of the more commonly used RBC drive systems have experienced operational problems. The most frequently occurring of these is misalignment of drive components, which contributes to accelerated component wear and operational failures. Other concerns include the maintenance of proper tension on belts in multi-V-belt systems to avoid accelerated wear of drive belts, and decreased drive efficiency and wear on chain-and-sprocket drives. Two of the 16 plants evaluated (3) reported broken drive chains.

BEARINGS

Six of the 16 plants evaluated (3) reported bearing failures. Some of the bearings in earlier designs were tapered roller bearings that required lubrication twice a week primarily to purge contaminants from the bearing race. Inadequate lubrication contributed to the failures observed. Current practice is to use self-aligning bearings with oversized grease cups to increase lubrication intervals.

SUMMARY

RBC systems have progressed through several generations of design. Systems presently being marketed have been improved compared to those surveyed. Only time will tell whether present systems will prove reliable for the contemplated project design life (normally 20 yr). Equipment reliability, consequences of failure, equipment specifications and warranties, and operational flexibility should be considered in all RBC designs. Design considerations are discussed further in Section 8.

SECTION 5

ORGANIC REMOVAL

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 glass fiber filters, which normally allow passage of particles up to about 0.3 to 2 μm depending on the particular filter used, that material passing the filter is generally defined as soluble. Primary effluent soluble BOD_5 typically represents from 40 to 60 percent of the BOD_5 loading to a secondary RBC system. Where fine screens are 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. Where an industrial source comprises a significant portion of the load on a municipal system, the ratio of soluble-to-total BOD_5 may vary widely from these typical values.

Soluble BOD loading is a key design parameter since smaller molecules can exert a more rapid biological organic demand than larger particulate materials (16). However, 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, and/or metabolize a substantial fraction of the incoming particulate material if a clarified final effluent of acceptable quality is to be achieved.

MASS TRANSFER OF OXYGEN AND ORGANICS

Under most circumstances, mass transfer is the dominant factor affecting organic removal in an RBC system. Mass transfer resistances associated with both the liquid phase and the biofilm result in significant concentration gradients from the bulk liquid to biological reaction sites in the biofilm. Oxygen transfer becomes limiting and controls the overall reaction rate in heavily loaded systems. The importance of mass transfer can be visualized by examining the changes depicted in Figure 6. Here the relative concentration of oxygen and organic substrate are shown at different media locations for one hypothetical loading condition and RBC speed. These relative values will, of course, vary for any particular set of design conditions. When the media are exposed to the atmosphere, the liquid film boundary at the air interface immediately becomes saturated with DO as shown for Point A in Figure 6. This saturation in turn results in an increase in the mass of oxygen that diffuses into the biofilm. When the media are 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

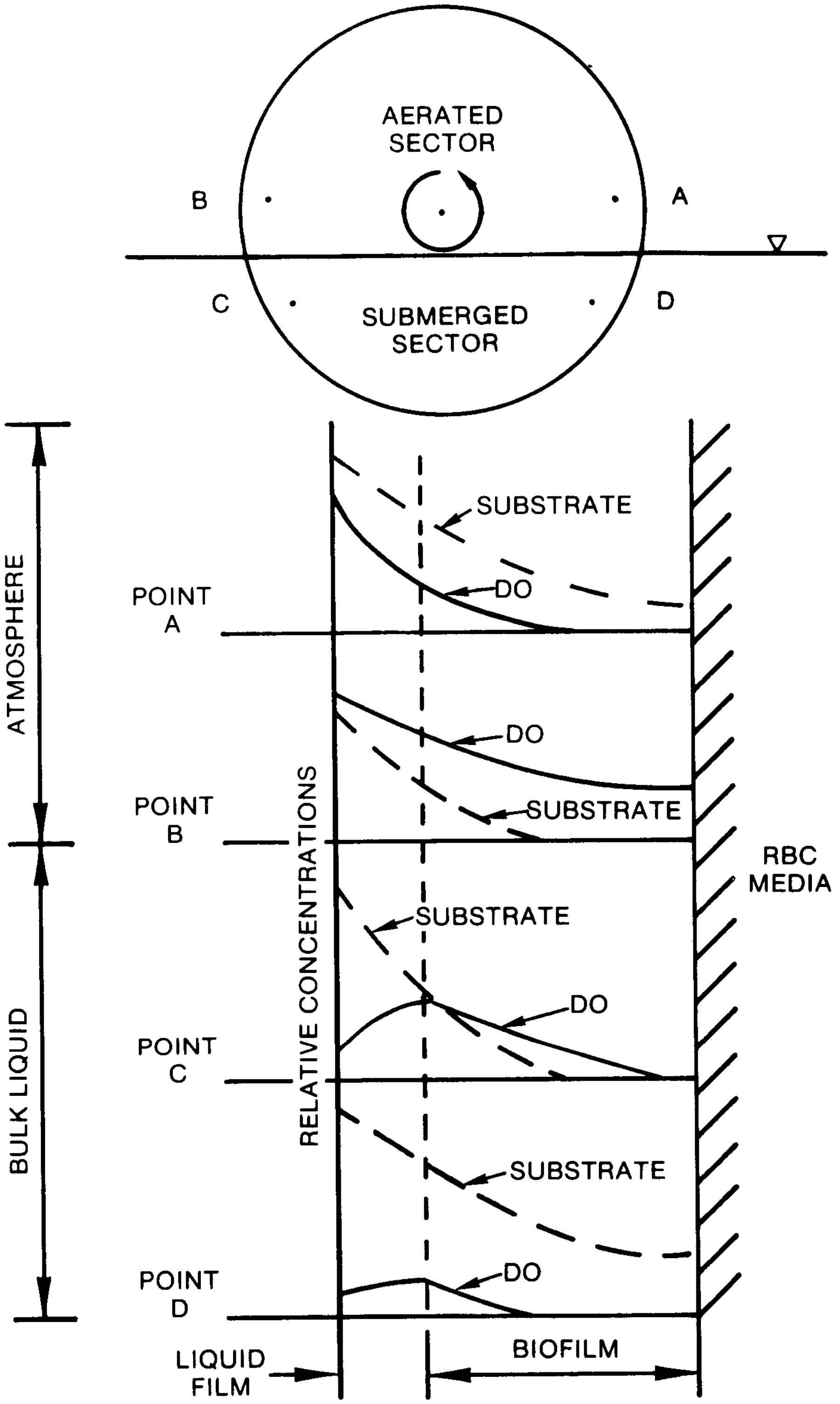

Figure 6. Relative concentrations of oxygen and substrate for one hypothetical loading condition and RBC rotational speed as a function of media location.

liquid. 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.

In addition to the oxygen transferred directly from the atmosphere to the nonsubmerged biofilm, oxygen also enters the bulk liquid as the result of turbulence generated by the rotation of the media and by the return to the bulk liquid of wastewater lifted into the atmospheric sector that flows freely back 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 atmospheric phase will increase the organic removal rate (17)(18)(19). Gas transfer from the air directly into the attached wastewater and biofilm represents the major oxygen source for the organisms. The beneficial effect on DO of compressed air injection in air drive RBCs is offset to some degree by their lower atmospheric oxygenation rates (compared to mechanical drive units) resulting from lower rotational velocities.

The total COD reduction across an RBC stage is a direct measure of oxygen transfer capability provided that nitrogen and sulfur species are not oxidized or reduced and influent and effluent DO levels are the same. Determination of total COD reduction requires that measurements be made on unsettled samples entering and exiting a stage so that the reductions represent those due to oxidative reactions only. COD balance studies conducted on a full-diameter RBC unit (20) indicated a maximum oxygen transfer rate of approximately 1.5 lb O_2/day/1000 sq ft. This maximum transfer rate was achieved at a rotational speed of about 1.6 rpm and is consistent with calculations of oxygen transfer based on observed nitrification rates in full-scale units (see Section 6).

The Autotrol design manual (7) 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 is possible for air driven units. Soluble BOD removal represents both the fraction removed through oxidative reactions and the fraction converted to new biomass. In the zero-order removal range, BOD removal is controlled by oxygen diffusion (7). Consider the data in Table 3 obtained on 11.8-ft diameter discs treating municipal wastewater. 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.

The above observations provide a background understanding of the key factors affecting substrate removal and oxygen transfer in RBC systems. When all of these factors are considered, it is apparent there is no reason to expect substrate removal from the RBC bulk liquid to follow any simple mathematical model. The maximum oxygen transfer and substrate removal rates indicated above are paramount in controlling RBC process performance and contribute to the basis of the empirical design procedures discussed in the following pages.

TABLE 3. FIRST-STAGE RBC DATA REPORTED BY HYNEK AND CHOU (21)

Run No.	Waste-water Temp. (°F)	Total BOD_5 Applied (lb/day / 1000 sq ft)	Mechanical Drive Soluble BOD_5			Total BOD_5 Applied (lb/day / 1000 sq ft)	Air Drive Soluble BOD_5		
			Applied (lb/day / 1000 sq ft)	Removed (lb/day / 1000 sq ft)	in Reactor (mg/l)		Applied (lb/day / 1000 sq ft)	Removed (lb/day / 1000 sq ft)	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

FIRST-STAGE LOADING LIMIT

A major constraint in the design of any RBC system is limiting the organic loading to the first stage(s) to values compatible with the oxygen transfer capability of the system. With excessive organic loadings, the biofilm thickness increases and a white/grey biomass is frequently observed.

Organic overloading is, therefore, characterized by the growth of an excessively thick biological film on the media surface and can be accompanied by or result in one or more of the following process performance and operational problems (22):

- DO deficit in the bulk liquid.
- Hindered oxygen transfer from the bulk liquid and air to interfilm layers on the RBC discs. In severe cases, bridging of biological growth between adjacent contactor discs can occur, effectively clogging the media and virtually stopping both oxygen and substrate transport.
- Anaerobic conditions within the biofilm leading to the dominance of undesirable microorganisms. For example, sulfide formed deep within the biofilm will diffuse outward and can lead to the proliferation of nuisance organisms such as Beggiatoa, accompanied by potentially reduced BOD removals.
- Development and predominance of microaerophiles throughout the biofilm and reduced BOD removal due to their lower metabolic rates.
- Creation of septic odors from both the bulk liquid and the biofilm.
- Elimination of the ability to control biofilm sloughing and thickness via liquid shearing forces.
- Increased energy requirements.
- Unbalanced structural loading, structural overloading, and structural failure of the media support framework and central shaft.

A survey of 23 RBC installations conducted for EPA related the presence of sulfur oxidizing organisms to overloading caused by high hydraulic loading and/or high influent BOD concentrations. The survey results are summarized in Figure 7 (1). It can be seen that a first-stage loading limit in excess of approximately 6.4 lb BOD_5/day/1000 sq ft was associated with the presence of sulfur oxidizing organisms.

Based on these findings, first-stage loadings in the range of 6 to 8 lb total BOD_5/day/1000 sq ft or 2.5 to 4 lb soluble BOD_5/day/1000 sq ft are considered to be acceptable (2). Loadings in the higher end of these ranges will increase the likelihood of developing problems such as heavier-than-normal biofilm thickness and nuisance organism growth, depletion of DO, and deterioration of overall process performance. The structural capacity of the shaft,

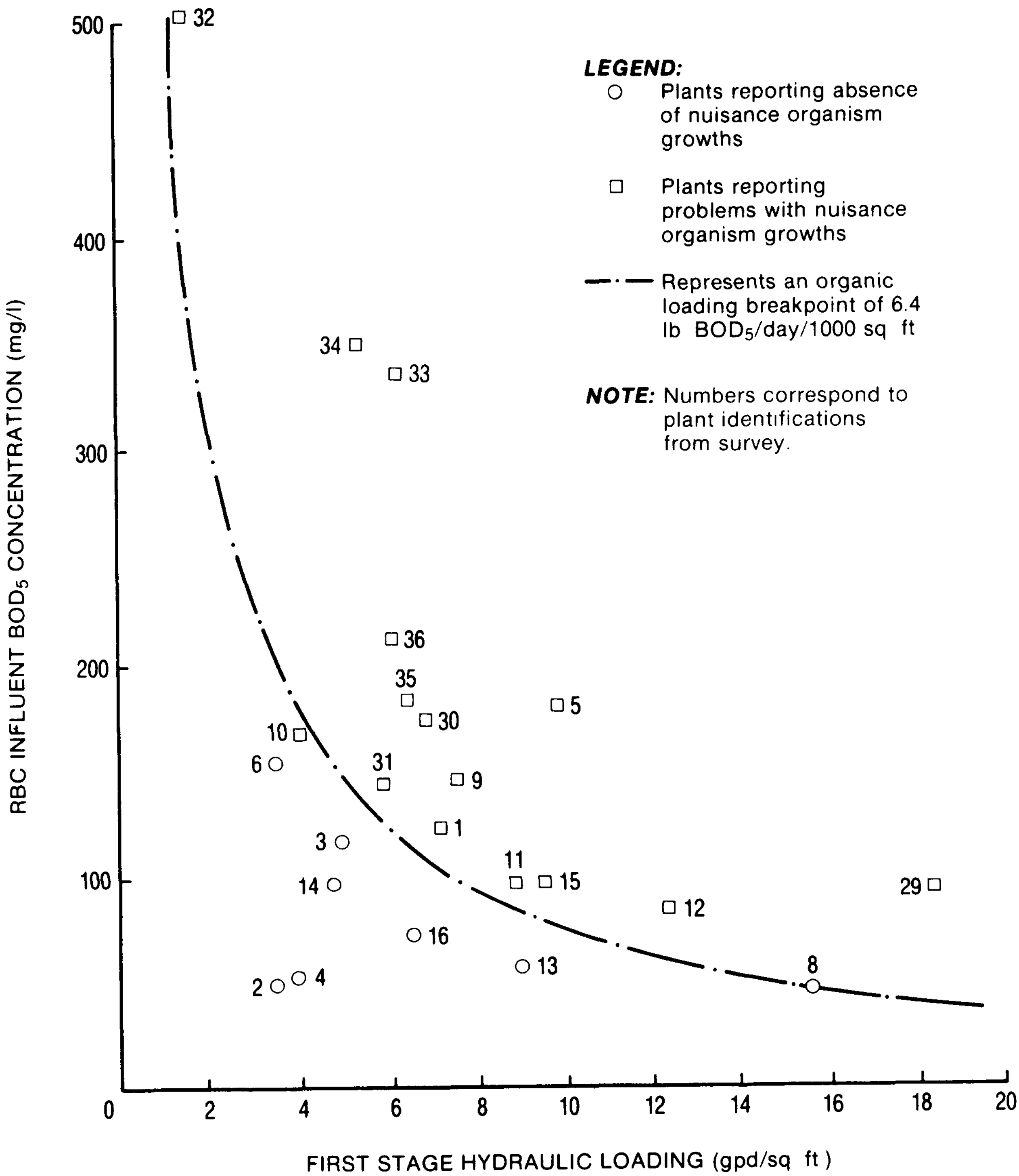

Figure 7. DO limiting conditions related to influent organic concentration and hydraulic loading [from Brenner et al. (1)].

provisions for stripping biofilm, consistently low influent levels of sulfur compounds to the RBC units, the media surface area required in the remaining stages, and the ability to vary the operating mode of the facility may justify choosing a loading in the high end of the range, but close attention must be given to process operations to minimize the possibility of structural overloading and/or operational problems.

DESIGN APPROACHES

Procedures for predicting organic removal relationships 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 and pilot and field data exhibit sufficient variation such that support for conflicting design approaches can usually be found.

Deterministic RBC Models

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 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 modeling 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.

Pilot Plant Studies

The best source of RBC design information is a comprehensive on-site pilot plant evaluation. A common design practice in the past has been to scale up small pilot plant results to full-scale applications by setting the media perpheral speed at the same value for both size units, i.e., normally about 60 fpm for mechanically driven units. More recent studies have shown that less-than-full-diameter units can exhibit greater removal capacities per unit surface area (23)(24). The use of full-scale diameter media is recommended in any pilot study to avoid scale-up problems. Insufficient information is presently available to accurately predict appropriate scale-up factors. 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-diameter unit to minimize scale-up problems.

Manufacturers' Design Procedures

RBC manufacturers have adopted guidelines related to various design parameters based on field experience. For example, most manufacturers have standardized tank volume-to-media surface area at 0.12 gal/sq ft based largely on studies (6) that indicated higher ratios did not improve BOD removal. The manufacturers have also found that loading variations do not adversely impact process performance at peak-to-average flow ratios of 2.5 or less. Two design manuals (7)(9) recommend utilizing peak flow and load conditions for design at ratios of 2.5 or less and flow equalization for ratios above 2.5. All manufacturers contend that wastewater temperature does not affect organic removal above wastewater temperatures of 55°F. Below this temperature, various correction factors are recommended as illustrated in Figure 8.

The number of stages utilized in an RBC design depends on several factors including effluent requirements, first-stage and overall process loading criteria, wastewater composition, and wastewater temperature, among others. General staging recommendations developed by three manufacturers are summarized below.

Envirex (7)		Clow (9)	Lyco (12)	
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	

The depth of design information provided on various aspects of RBC organic removal differs considerably among the various manufacturers. To provide perspective on the range of predicted performance that results from using these 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 are presented in Figure 9. The three Lyco predictions are based on total influent BOD_5 concentrations of 100, 150, and 225 mg/l. Both Envirex and Clow predict identical relationships for the loading ranges examined. Published design procedures for Crane-Cochrane and Walker Process are not available. In lieu of establishing published design procedures, both firms have indicated they prefer to evaluate wastewater characteristics and process requirements of potential clients on an individual basis before recommending specific loading criteria and projecting anticipated performance.

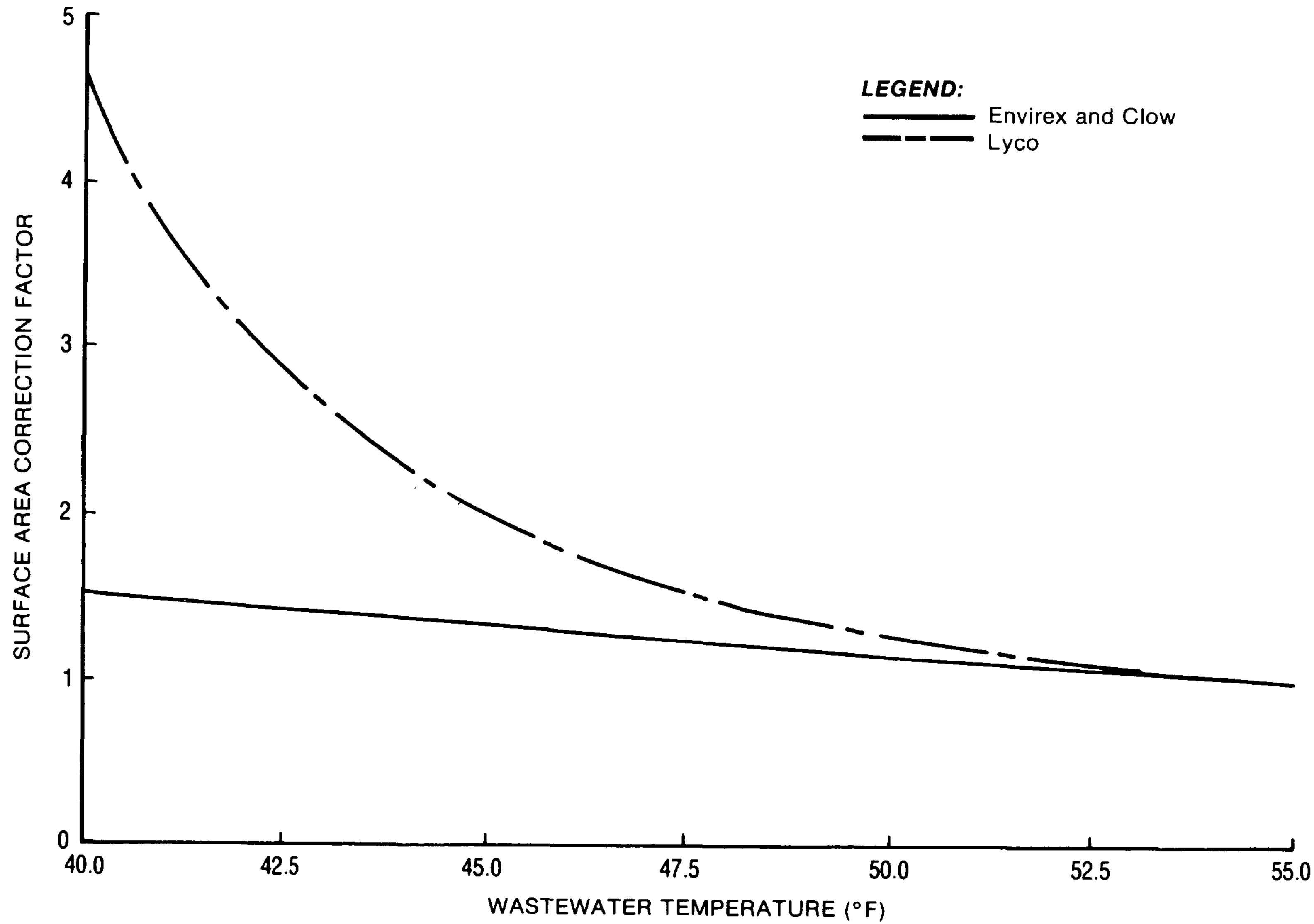

Figure 8. Manufacturer temperature correction factors for BOD_5 removal [from Roy F. Weston (25)].

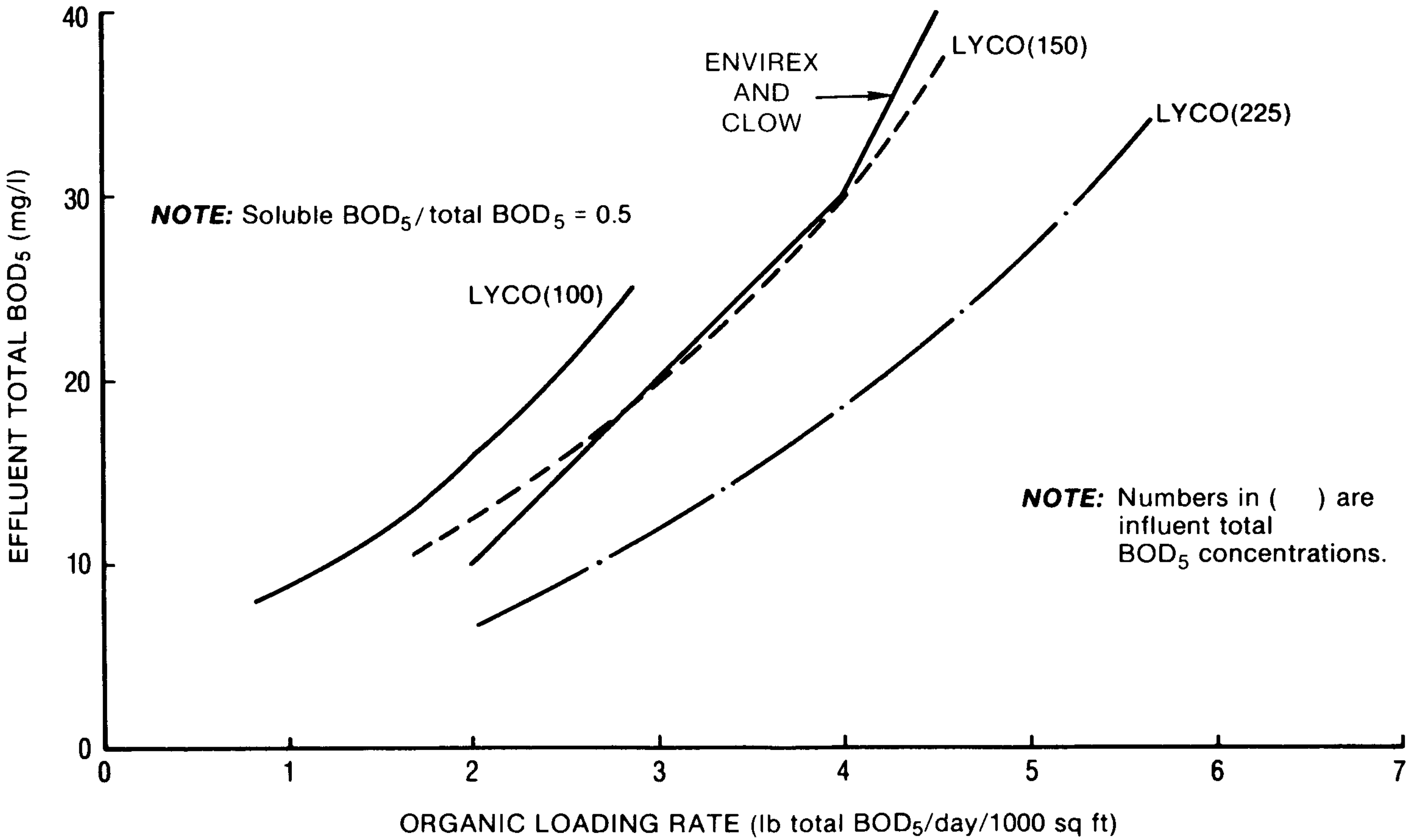

Figure 9. Effluent BOD_5 as a function of organic loading for selected RBC manufacturers design techniques.

Alternative Design Approach

In an attempt to devise an improved method of organic removal estimation, Opatken (26) evaluated soluble organics interstage data by using the following equation for a second order reaction (27):

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

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). Interstage and final effluent soluble BOD_5 values predicted using this expression were compared against measured values obtained at nine full-scale air drive plants. A k value of 0.083 was used for all installations. The predicted and measured values were in good agreement for seven of the nine plants as shown by the representative results in Figure 10. The lack of close agreement at one plant could be explained by inadequate oxygen transfer in the first stage to handle the high influent organic load; the lack of close agreement at the other plant could not be explained.

The second-order predicted values in general more closely approximated measured soluble BOD_5 concentrations than did values predicted by Envirex's empirical organic removal design method for air driven RBCs. These results indicate that second-order kinetics may offer an improved basis for predicting interstage soluble organic removals in RBC systems that are not oxygen transfer limited. As with the manufacturers' empirical techniques, the second-order kinetics approach only addresses the impact of soluble organics on effluent quality.

SECONDARY CLARIFICATION

The concentration of unsettled suspended solids (SS) 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. A number of investigators have undertaken studies of surface overflow rates of secondary clarifiers used in conjunction with RBCs to achieve certain desired effluent qualities. The following is a summary of the findings of some of those studies:

Surface Overflow Rate (gpd/sq ft)	Performance Objective	Reference
550-650	<30 mg/l SS	Scheible and Novak (20)
740	>80% SS removal	Srinivasaraghavan et al. (28)
<600	Maximize solids removal	Murphy and Wilson (24)
800	30 mg/l SS (t.f. upgrade)	Smith et al. (29)
500	15 mg/l SS (t.f. upgrade)	Smith et al. (29)
800	30/30 effluent	Clow (9)
≤500	10 mg/l SS	Clow (9)
1000-1200	Peak hydraulic rate	DeCarlo (30)

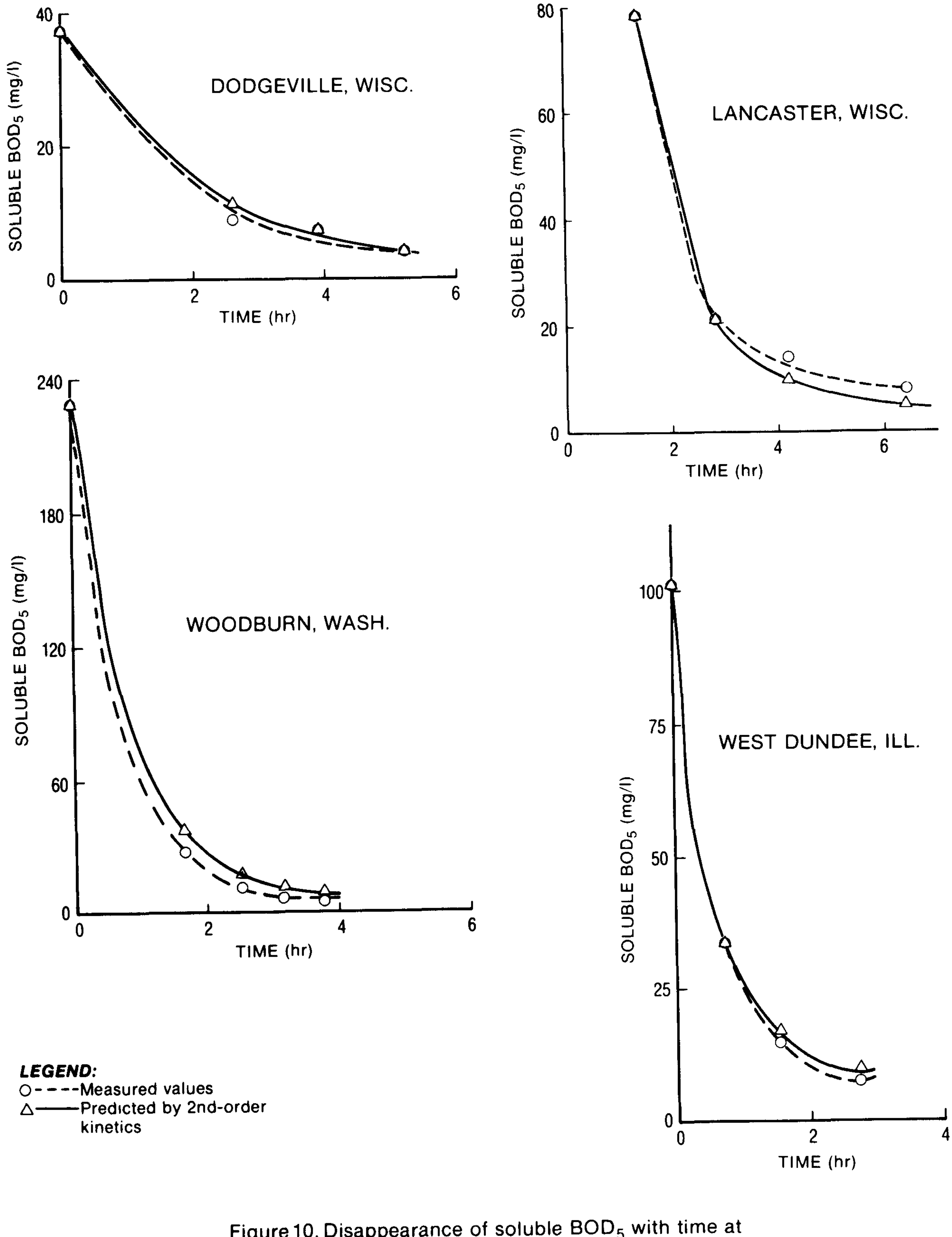

Figure 10. Disappearance of soluble BOD_5 with time at four representative RBC plants.

SECTION 6

NITRIFICATION

INTRODUCTION

The factors affecting nitrification in the RBC process include influent organic concentration, influent nitrogen concentration and composition, wastewater temperature, DO concentration, pH and alkalinity, and influent flow and load variability, among others. Because of the varying degrees of hydrolysis that can occur in sewer lines, RBC nitrification designs should not be based on influent ammonia nitrogen concentration alone. To do so risks serious undersizing if substantial amounts of organic nitrogen are present. One manufacturer (31) recommends basing design on influent soluble TKN (mg/l) minus 0.10 x soluble BOD_5 removed (mg/l) to account for heterotrophic nitrogen metabolism. A less empirical approach is to base design on influent total TKN (mg/l) minus 1.0 mg/l refractory soluble organic nitrogen minus 0.055 x soluble BOD_5 removed, which assumes a yield factor of 0.6 and a cell nitrogen content of 9.2 percent to estimate heterotrophic nitrogen metabolism (1).

The impact of flow and mass loading variations is usually more severe on the nitrification efficiency of RBCs than on their organic removal performance. Nitrifiers have long generation times compared to heterotrophs. Further, external accumulation and/or internal storage of ammonia nitrogen for delayed metabolism does not take place with nitrifiers. Consequently, influent surges in flow or unoxidized nitrogen concentrations will be accompanied by similar, delayed (roughly equal to reactor detention time) spikes of unoxidized nitrogen in the effluent unless adequate RBC surface is provided to compensate for expected variations. Where consistently low effluent ammonia nitrogen residuals are required, flow equalization may be cost effective.

INFLUENCE OF ORGANICS

The normally 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 heterotrophic bacteria will predominate in an RBC biofilm when the organic concentration is high. 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. Selective predation of nitrifying bacteria by higher life forms has been observed in tail-end RBC stages where high DO concentrations (6 to 8 mg/l) and low soluble BOD_5 levels (<5 mg/l) can coexist. Sullivan (31) recommends limiting tail-end DO's to 3.5 mg/l through reduced media rotational velocity, if possible, to discourage predation of nitrifiers.

Most empirical design procedures (7)(9)(12) are based on the assumption that significant nitrification doesn't begin in an RBC system until bulk liquid soluble BOD_5 has been reduced to 15 mg/l. In combined carbon oxidation-nitrification units, BOD_5 values of this magnitude may first be encountered in the second, third, or fourth stages, depending on influent strength, organic loading rate, and wastewater temperature. In separate-stage nitrification applications, the soluble BOD_5 concentration of the wastewater entering the RBC reactor is usually well below 15 mg/l and substantial nitrification is evident in the first stage. Analysis of field data indicates that while incipient nitrification is generally observed in RBC stages with soluble BOD_5 concentrations of about 15 mg/l, maximum nitrification rates are not attained until bulk liquid soluble BOD_5 drops to 10 mg/l or less (1).

NITRIFICATION RATES

Extensive testing and data evaluation were conducted by Autotrol to model ammonia nitrogen oxidation in RBCs. The current Envirex procedure for full-diameter RBC units operating at wastewater temperatures of 55^oF or greater is based on prior Autotrol testing and is summarized graphically in Figure 11. This curve 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 zero-order rate of approximately 0.3 lb NH_3-N/day/ 1000 sq ft. It is interesting to note that a nitrification rate of 0.3 lb NH_3-N/day/1000 sq ft represents an oxygen demand of about 1.4 lb/ day/1000 sq ft, which corresponds closely with the estimates made by Scheible and Novak (20) (see Section 5). Hence, the nitrification rate of 0.3 lb NH_3-N/day/1000 sq ft in full-scale systems is apparently the result of oxygen transfer limitations.

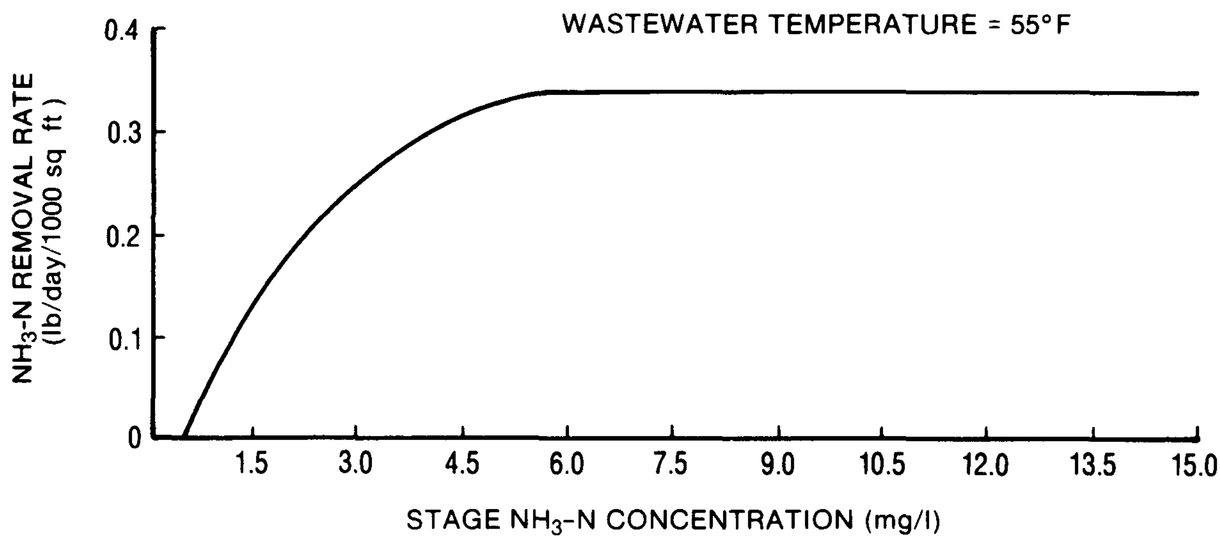

Figure 11. Second-generation Envirex ammonia nitrogen removal rate curve for full-scale RBCs [from Antonie (6)].

Designs for nitrification using RBCs are often based on pilot-scale testing. Although some pilot studies have reported nitrification rates as high as 0.7 lb NH_3-N/day/1000 sq ft (32)(33)(34), it should be noted that rates this high are not attainable with full-diameter units rotating at 1.6 rpm. As with organic removals, higher inherent rates of atmospheric surface renewal and oxygen transfer associated with increased rotational velocity explain the observed differences between small-diameter and full-diameter units rotated at the same tip speeds.

Nitrification data obtained at three full-scale facilities when wastewater temperatures were 55 $\pm$ 2°F are shown in Figure 12. Each point represents data for 1 day for a given stage. For the combined carbon oxidation-nitrification systems (Gladstone, Michigan, and Cleves, Ohio), ammonia nitrogen removal data prior to the stage in the train where maximum nitrification rates were observed were omitted on the assumption that organic removals were influencing the nitrification rates. The curve shown in this figure essentially duplicates the curve used in the current Envirex procedure. The zero-order removal rate above bulk liquid ammonia nitrogen concentrations of 5 mg/l corresponds to 0.3 lb NH_3-N/day/1000 sq ft.

If all other factors are not rate limiting, e.g., pH, DO, and/or oxygen transfer, an increase in temperature above 55°F would be expected to increase the NH_3-N oxidation rate observed in RBC systems. Field data from five nitrifying plants operating at higher wastewater temperatures (65 $\pm$ 5°F) are plotted in Figure 13. While the data are more scattered than in the 55 $\pm$ 2°F plot, the average removal rate at concentrations above 5 mg/l NH_3-N is actually no higher than the 0.3 lb NH_3-N/day/1000 sq ft rate estimated at 55°F. Comparison of Figures 12 and 13 supports the manufacturers' contention that wastewater temperatures above 55°F do not result in higher nitrification rates on full-scale units. The probable explanation for this phenomenon is that above 55°F oxygen transfer capacity rather than biological growth rate controls the maximum nitrification rates attainable in full-scale systems.

Low wastewater temperature (47 $\pm$ 2°F) nitrification data were available for Gladstone (35). Evaluation of these data indicated that an estimate of the amount of additional media surface area required to achieve an effluent ammonia nitrogen level of 1.5 mg/l at 47°F compared to 55°F was identical to or within 10 percent of that predicted by the temperature correction curves of Envirex, Clow, and Lyco illustrated in Figure 14. These data indicate that as wastewater temperature drops increasingly below 55°F, biokinetic response displaces oxygen transfer capacity as the dominant factor controlling full-scale nitrification rates.

Nitrification rates can be significantly affected by pH, particularly in unacclimated systems. One study (32) where pilot RBC units were allowed to acclimate to each pH level tested reported 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. On another RBC pilot study (34), increasing nitrification rates were observed as pH was increased from 6.5 to 8.5 Nitrification enhancement with increasing pH values above the typical pH range for raw wastewater of 7.0 to 7.5 has never been demonstrated, however, on full-scale RBCs. As with wastewater temperature, oxygen transfer limitations may

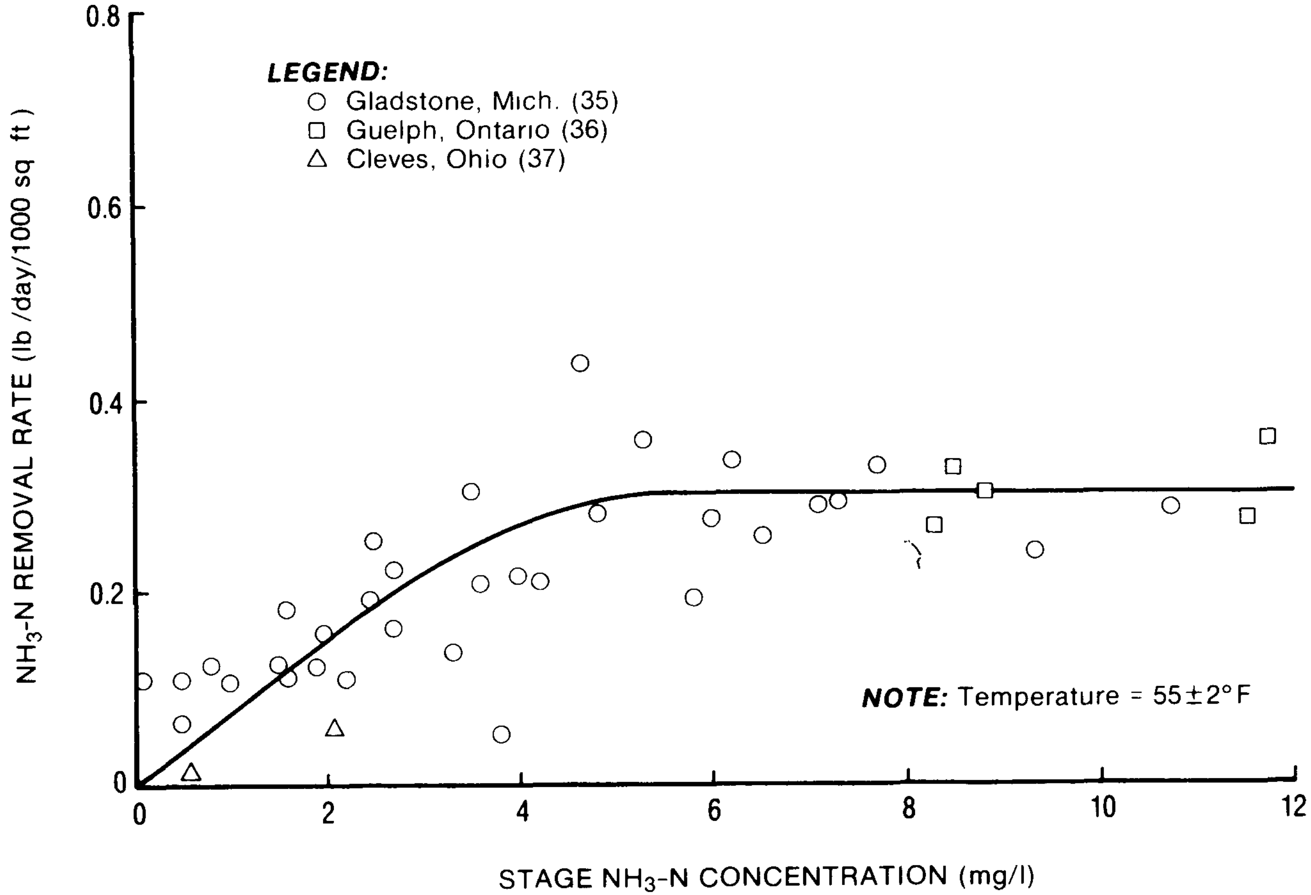

Figure 12. Full-scale RBC nitrification rates at design wastewater temperature (55° F).

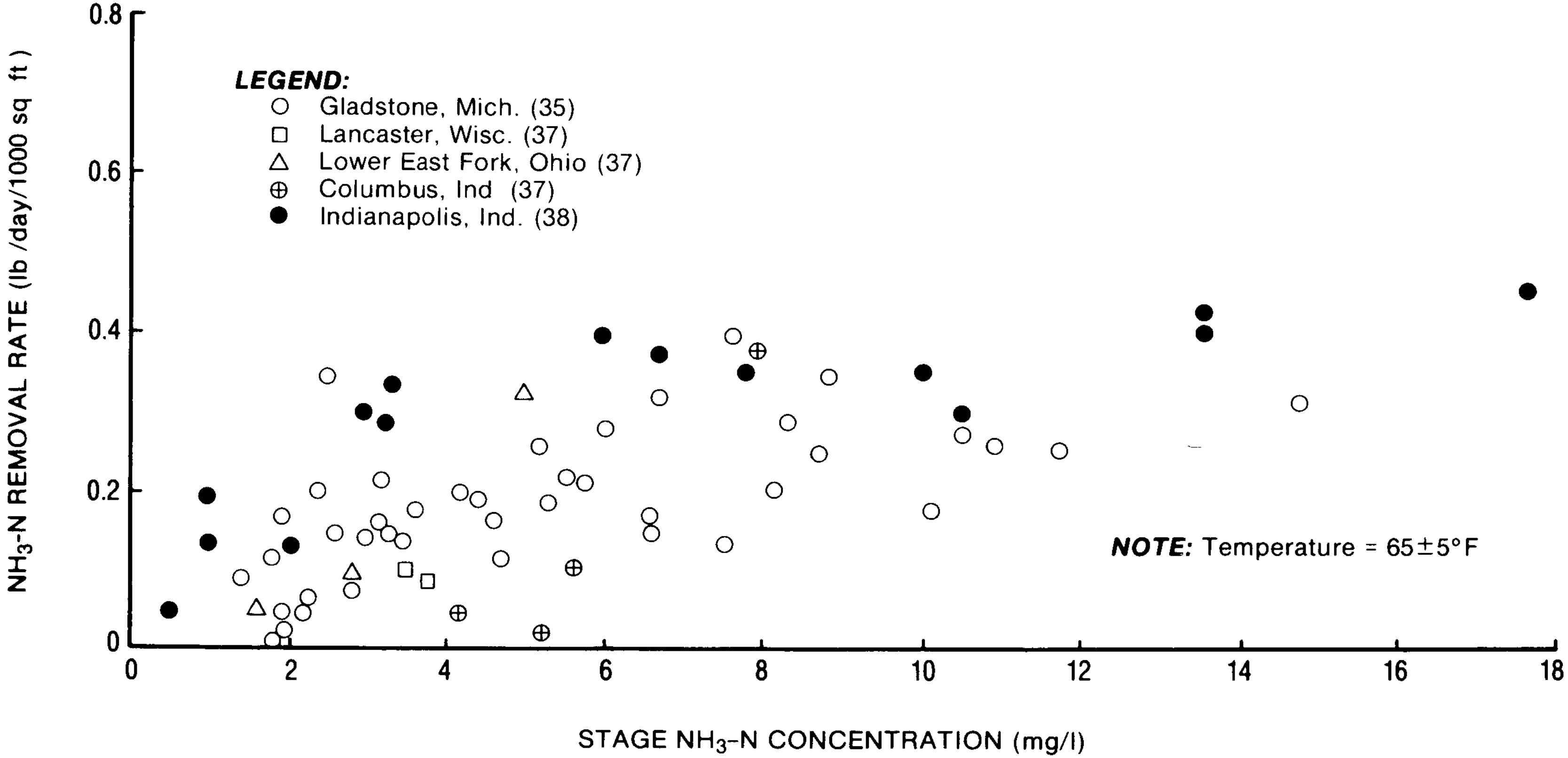

Figure 13. Full-scale RBC nitrification rates at high wastewater temperatures.

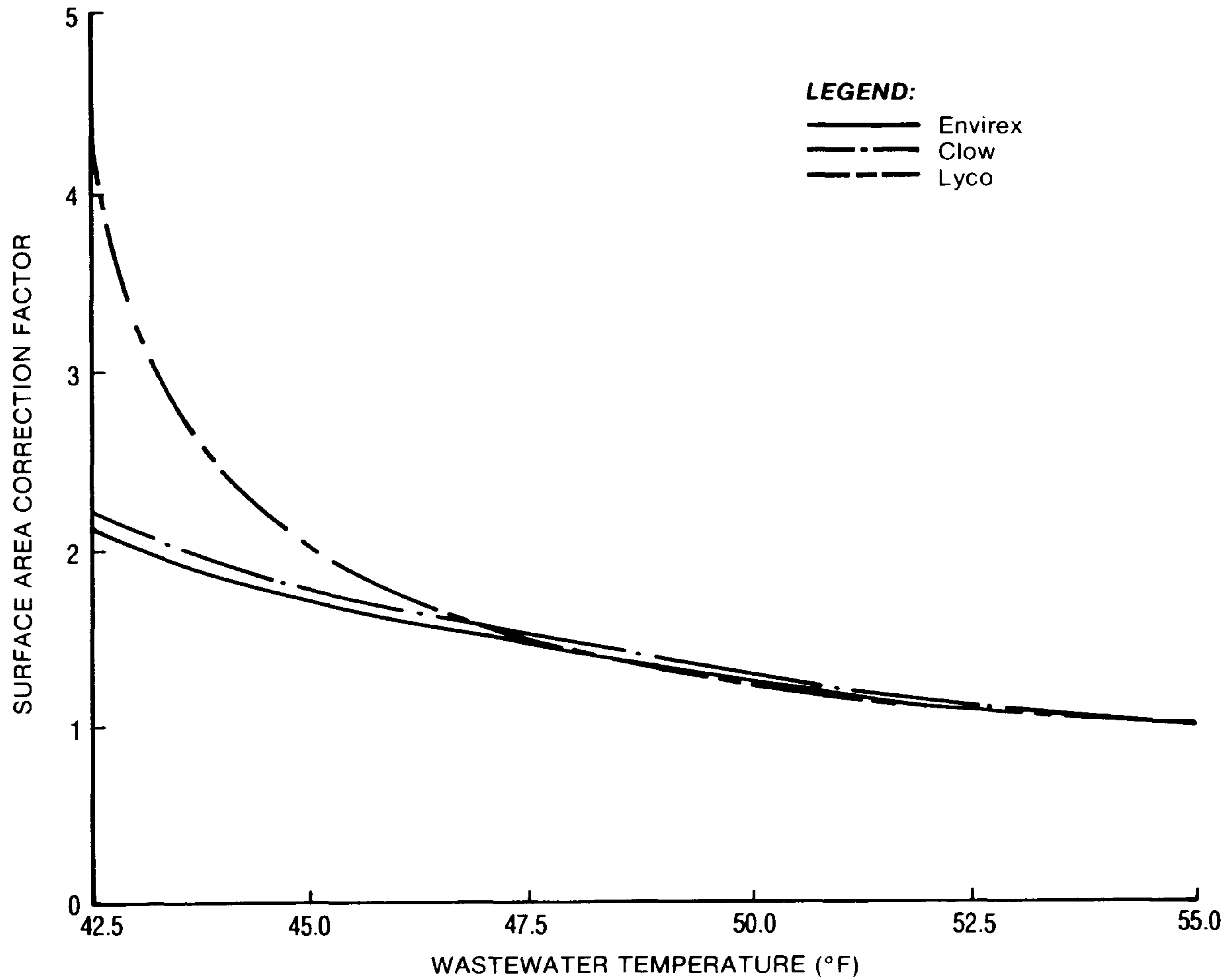

Figure 14. Manufacturer temperature correction factors for nitrification [from Roy F. Weston (25)].

obscure pH optimization of nitrification in 12-ft diameter field units rotated at 1.6 rpm.

The process of nitrification consumes alkalinity. In poorly buffered RBC nitrifying systems, alkaline chemicals such as lime, soda ash, or sodium hydroxide may have to be added to the wastewater to maintain sufficient alkalinity to prevent a precipitous drop in pH and nitrification rate.

SECTION 7

ENERGY REQUIREMENTS

INTRODUCTION

Energy 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 force, which constitutes the major portion of the energy required for shaft rotation, is affected by the amount of media surface area, the shape of that surface area, rotational speed, wastewater viscosity (temperature), and the type and amount of biological growth.

With air driven systems, compressed air is discharged beneath the RBC media as previously shown in Figure 4. The rising air is captured by the air cups, and the resulting buoyant forces provide the torque necessary for media rotation. Energy 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.

MECHANICAL DRIVE SYSTEMS

Manufacturers' estimates of energy requirements for mechanical drive units rotating at approximately 1.6 rpm are as follows (39):

	Media Type	
Manufacturer	Standard Density (kW/shaft)	High Density (kW/shaft)
Clow	2.1	2.4
Envirex	1.55(1.8)[a]	2.3(2.6)[a]
Lyco	-	1.7 - 2.1
Walker Process	2.0(2.6)[b]	2.3(3.0)[b]

[a] First number is mean of field measured values; second is 99.9 percent confidence level.
[b] First number is average value; second is maximum value.

Environmental Resources Management, Inc. (ERM), conducted an extensive EPA sponsored field investigation to determine actual energy requirements on a total of 105 mechanically driven units (4). A variety of shaft lengths, media surface areas, and manufacturers' equipment were included in the study. A summary of all field measured data is given below:

Motor Size (hp)	kW/Shaft	
	Average	Range
5	2.02	1.05 - 3.76
7.5	2.05	1.32 - 2.99

Data from 80 of the units tested by ERM were selected as representative of facilities with typical shaft lengths, media diameters, and rotational speeds. These data were combined with data from 12 units evaluated by EPA staff (40) to ascertain the impact of media surface area on energy requirements. Of these 92 units, a total of 55 were equipped with media having a surface area in the range of 100,000 to 128,250 sq ft, a range 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 energy consumption for the standard density units was 2.09 kW/shaft with a standard deviation of 0.46 kW/shaft. For the high density units, the average power requirement recorded was 2.40 kW/shaft with a standard deviation of 0.59 kW/shaft. These values agree well with the manufacturers' estimates of mechanical drive energy requirements.

Excessive energy consumption is generally indicated when field-measured power levels exceed by one to two standard deviations the means indicated above for standard and high density media. Higher-than-expected energy consumption can be caused by equipment problems, heavier-than-normal biofilm growth, or both. Potential equipment problem areas include improper belt alignment, inadequate lubrication, excessive rotational speed, excessive belt tension or belt slippage, and general wear and deterioration of the drive components.

Power factor is an important parameter in determining the energy cost associated with operating an induction motor. Many electric utilities have demand charge schedules that penalize customers with power factors less than 0.9. The power factors for mechanically driven RBC units are typically quite low as indicated by the following data from the 92 units summarized above:

Surface Area Range (sq ft)	Motor Size (hp)	Power Factor	
		Mean	Range
100,000 - 128,250	5	0.51(28)[a]	0.26 - 0.71
100,000 - 128,250	7.5	0.38(27)[a]	0.18 - 0.82
138,000 - 180,000	5	0.49(20)[a]	0.26 - 0.68
138,000 - 180,000	7.5	0.38(17)[a]	0.16 - 0.63

[a] Number of shafts.

The Upper Mill Creek (Cincinnati, Ohio) treatment plant utilizes mechanically driven RBC units equipped with power factor correction capacitors. Measurements made on seven units with power factor correction indicated that the capacitors were increasing power factor from about 0.5 to 0.99 (1). The resulting savings in apparent power are worth $17.30/month/shaft in lower electrical costs at an assumed demand charge of $6.92/month/kVA. Based on an approximate installed capacitor cost of $200, the payback period in this case would be about 12 mo.

AIR DRIVE SYSTEMS

The energy 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 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. The usual industrial practice is to design for headlosses in the range of 0.1 to 0.6 psi/100 ft of line. It is important that the design conditions stipulated for the centrifugal compressors match actual operating conditions as closely as possible. Compressor operation at conditions other than those for which the compressor was designed can result in a substantial loss of efficiency. For those facilities in which significant variations in air flow requirements are anticipated, consideration should be given to using multiple compressors with different design capacities, both for air flow and discharge pressure.

The air flow requirements to operate an air-driven RBC system are variable. Envirex (31) recommends that 350 cfm of capacity be provided for each shaft. The maximum normalized air flow at ambient conditions (68°F) with 4-in. air cups for various rotational velocities is presently indicated by the manufacturer to be as follows (41):

	Air Flow (acfm[a]) 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

[a] acfm = actual cfm

The actual air flow requirements to operate a shaft at a given speed are also reported to vary by 40 to 80 acfm, and the mean requirement over a range of 1.0 to 1.3 rpm will vary more than this (42).

Results of an EPA study (40) that evaluated the relationship between rotational speed and air flow requirements for one process train at the Lower East Fork (Batavia, Ohio) plant are presented in Figure 15. Also shown are the manufacturer's design curves (41) for the range of conditions applicable

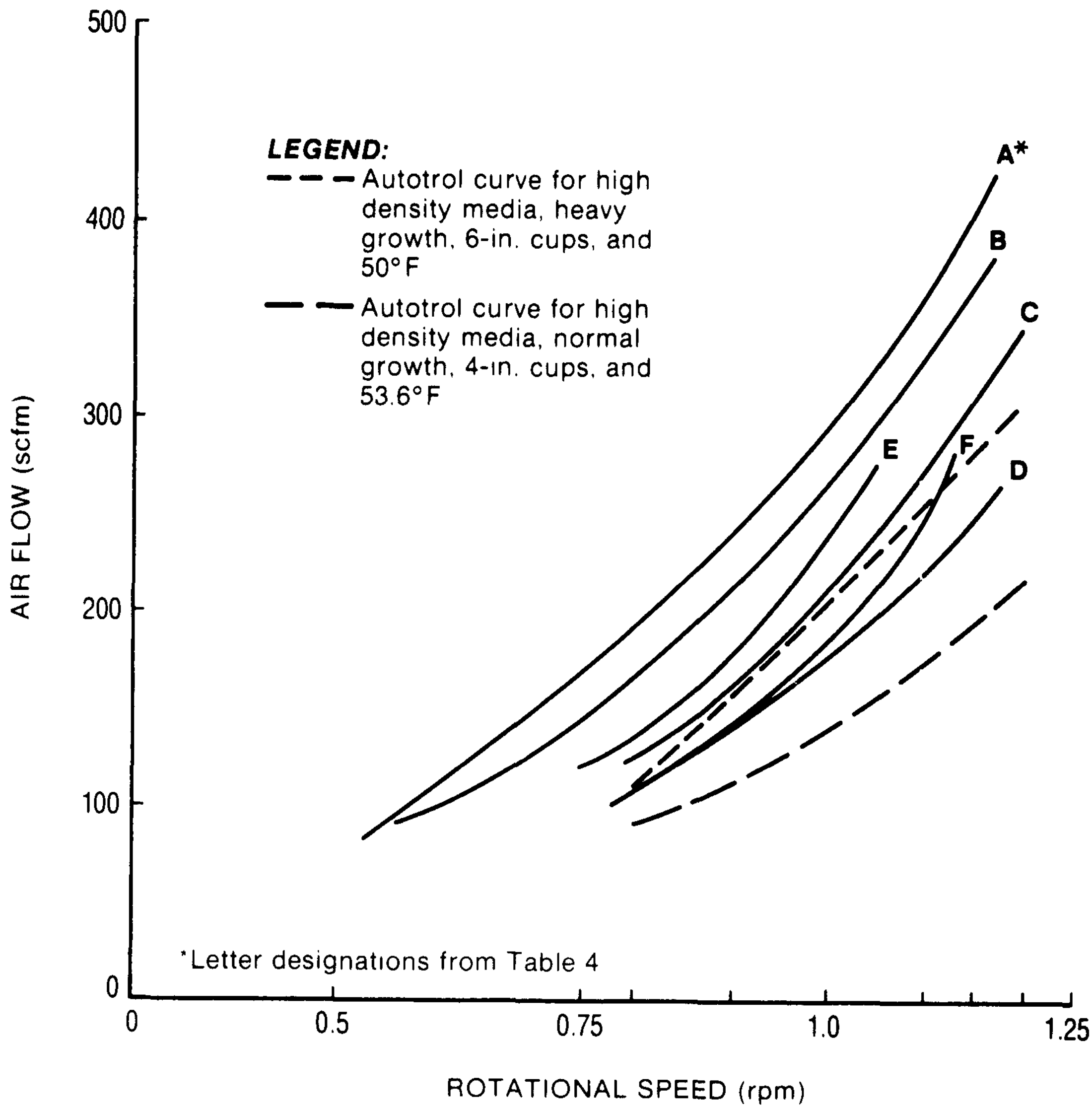

Figure 15. Summary of air flow versus rotational speed measurements made at Lower East Fork-Little Miami River Regional Wastewater Treatment Facility, Claremont County, Ohio.

to the measurements made at this site. The operating conditions under which the data represented by curves A to F were generated are summarized in Table 4. It can be seen that air flow requirements for a given rotational speed are highly variable and unpredictable (compare curves B and C). The specific energy requirements for an air driven RBC facility can only be determined on a case-by-case basis.

TABLE 4. SELECTED OPERATING CONDITIONS OF LOWER EAST FORK PLANT

Curve Designation in Figure	Air Cup Depth (in.)	Stage	Date Measured (1982)	Biofilm Thickness (in.)
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	-

SECTION 8

PLANT DESIGN CONSIDERATIONS

INTRODUCTION

Proper design of an RBC facility entails, among other things, accurate determination of influent and sidestream loadings, proper media sizing, staging and equipment selection to meet effluent requirements, and selection of an overall plant layout that provides sufficient flexibility to promote good operation and maintenance practices. A number of design considerations (in addition to those discussed in the preceeding sections) are germane to the quality construction and successful operation of an RBC installation.

PRETREATMENT

Raw municipal wastewater should not be applied to an RBC system. Effective preliminary treatment is essential for good operation. Grit removal and either primary clarifiers or screens are necessary to remove materials that may settle in the RBC tankage or plug the RBC media. High influent grease loads require the use of primary clarifiers or an alternate system for grease removal prior to the RBC units.

The impact of sidestreams from other unit processes must be considered. Anaerobic digesters increase ammonia nitrogen loadings, and sludge conditioning processes such as heat treatment contribute increased organic and ammonia nitrogen loadings. Where septage addition is to be allowed, separate facilities for its acceptance and controlled feeding to the RBC system should be considered. Septic tank waste addition or a separate unit process located ahead of the RBC system that has the potential for sulfide production, e.g., clarigesters, produces an incremental oxygen demand associated with the sulfide that must be considered in system design.

EQUIPMENT SPECIFICATIONS, MAINTENANCE, AND RELIABILITY

The suggested ranges for first-stage organic loading rates as presented in Section 5 are based on both process and structural considerations. First-stage loadings in the upper end of the range may result in a variety of operational and process problems, of which the most critical is the structural overloading of the RBC shaft. Over the life of a facility, organic loadings will vary considerably and excessive biofilm growths can frequently occur. Therefore, the specifications for the load bearing capacity for each shaft should consider the maximum anticipated biofilm growth, the capacity to strip excess biofilm, and an adequate margin of safety. In addition, structural designs of RBC shafts should be based on appropriate AWS stress category curves (14)(see

Section 4) modified as necessary to account for the expected corrosive environment.

Full building enclosures normally provide more convenient access to RBCs for routine maintenance and visual observation than the use of individual fiberglass covers. Housing RBC units within a building is undesirable, however, because of the corrosive atmospheric conditions associated with the presence of hydrogen sulfide and high humidities. Condensation problems have been encountered on interior building walls in cold climates, and the accompanying high humidities and ventilation requirements increase heating costs. Where buildings are chosen, the building design must meet the additional requirements for ventilation, heating, and humidity control, and provide for removal of a shaft/media assembly should repair or replacement prove necessary.

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. 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, whereas others do not (see Section 3). Where all units in a large installation are physically located closely 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.

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. Specifications can set strict warranty requirements. Careful thought needs to be given to the acceptability of field repairs versus new factory replacement equipment, as well as other areas of potential conflict. Considering the history of equipment failures, the specification of a rigorous performance and replacement guarantee may offer the best protection available to the treatment plant owner.

FLOW CONTROL

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 bypass these terminal units would result in energy and O&M savings. If sufficient flow flexibility is available, loss of an individual unit need not result in shutting down an entire process train. Adjusting the distribution of total flow and/or loading may be an operational necessity, again emphasizing the need for positive and measurable flow control and/or splitting.

The use of deep channels leading to and exiting from RBC tanks often results in solids deposition and subsequent accumulation. Providing for channel aeration (3.5 scfm/linear ft) 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 against 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.

BIOMASS MONITORING AND CONTROL

Organic loading limits and detrimental impacts resulting from organic overloads were previously presented in Section 5. 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. Load cells (see Section 3) located at these and other strategic locations can provide the operator with advance notice of a gradual buildup in biofilm thickness.

DO monitoring is another operational tool that can be used advantageously for process control. Falling stage liquor DO levels, particularly in the lead stages, may forewarn of conditions conducive to the growth of undesirable organisms and the development of excessive biofilm thicknesses. However, increasing DO levels in the bulk liquid by itself will not necessarily overcome process performance difficulties that may have developed and other actions to strip excess biofilm may be required. Two of the plants surveyed by Roy F. Weston, Inc., had nuisance organisms (Beggiatoa) present in the first stages despite bulk liquid DO levels of 1.5 to 2 mg/l (3). A similar observation was also made at the RBC facility in Edgewater, New Jersey (20). A major advantage of the air drive RBC system is claimed to be related to the increased turbulence and stripping of excess biofilm induced as a portion of the air bubbles rise through the media.

Sufficient operational flexibility must be provided to allow effective response to organic overloads. Possible corrective action includes increasing rotational speed to enchance oxygen transfer and biofilm shearing force, periodically reversing the direction of RBC rotation to promote biofilm stripping, using supplemental aeration to increase bulk liquid DO concentration and induce biofilm stripping, increasing media surface area in the affected stage by removing baffles to reduce overall loading, staging feed of incoming flow, and temporarily adding chemicals such as hydrogen peroxide or chlorine.

MISCELLANEOUS CONSIDERATIONS

As discussed in Section 5, influent soluble BOD is a critical parameter in the design of RBC units. In the design of any facility, soluble BOD levels should be verified by influent sampling whenever possible.

Depending on whether the media formulation includes 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.

High density media has been used advantageously in the middle and latter stages of RBC trains where decreased availability of organic carbon results in biofilm thicknesses of <50 mils (0.05 in.). 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.

Air drive installations should be provided with positive air flow metering and control to each RBC unit. Operating an air drive facility without these controls adds to the difficulty of appropriately responding to operational problems that may arise.

Stop motion detectors, rpm indicators, and clamp-on ammeters are potentially useful monitoring devices for individual RBC shafts.

Energy requirements for RBC rotation increase exponentially with rotational speed. Previous tests with clean media have shown that power consumption increases as a cubic function of rotational velocity (3). Other energy-consuming factors exist independent of speed, however. Accordingly, the cubic relationship should not be used indiscriminately.

Nitrification is slow to develop in cold temperatures, and 8 to 10 wk may be required before a nitrification system approaches equilibrium conditions. Where seasonal standards are required for the final design, the transition time and temperatures necessary to develop an adequate nitrifying population must be considered.

O&M requirements associated with biofilm control, drive train and radial support arm maintenance and repair, and media and shaft repairs and replacements should be considered in laying out the RBC process configuration and selecting equipment. The O&M manual should specify a schedule for reading load cells, visually inspecting biofilm growth and media integrity, and determining the status of mechanical and structural components. The manual should also outline procedures for dealing with identified problems.

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