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Technology Assessment of the Deep Shaft Biological Reactor

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TECHNOLOGY ASSESSMENT
OF THE
DEEP SHAFT BIOLOGICAL REACTOR

by

Roy F. Weston, Inc.
West Chester, Pennsylvania 19380

Contract No. 68-03-2775

Project Officer

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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. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components re-require a concentrated and integrated attack on the problem.

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

The innovative and alternative technology provisions of the Clean Water Act of 1977 (PL 95-217) provide financial incentives to communities which use wastewater treatment alternatives that reduce costs or energy consumption over conventional systems. Some of these technologies have been only recently developed and are not in widespread use in this country. In an effort to increase awareness of the potential benefits of such alternatives and to encourage their implementation where applicable, the Municipal Environmental Research Laboratory has initiated this series of Emerging Technology Assessment reports. This document discusses the applicability and economic feasibility of utilizing the Deep Shaft Biological Reactor for municipal wastewater treatment facilities.

Francis T. Mayo
Director
Municipal Environmental
Research Laboratory

ABSTRACT

One of the recent changes in the Federal funding policy for municipal wastewater treatment facilities requires the analysis and evaluation of innovative and alternative technologies during the development of wastewater management alternatives. The objectives of this requirement are:(1,2)

1. To incorporate more cost-effective and energy-efficient systems in publicly-owned treatment works (POTW's) than those utilizing traditional or conventional design practice.

2. To encourage innovative and alternative processes that provide for the reclamation and reuse of wastewater.

3. To encourage the utilization of recycling techniques, land treatment, and new and improved hazards of joint municipal and industrial treatment.

This requirement, administered through the Environmental Protection Agency's (EPA) Construction Grants Program, has encouraged the development of several new processes having potential for application in municipal wastewater treatment practice. In order to assess the status of development and the capabilities of these "emerging" technologies, EPA has initiated a series of technology assessments for evaluating these processes. This technology assessment report is prepared to evaluate the "Deep Shaft" biological treatment process which is currently under various stages of development and application.

The Deep Shaft biological treatment process is essentially a high-rate activated sludge process capable of operating at BOD_5 loading ratios (F/M) between 0.5 and 2.0 kg BOD_5/kg MLVSS.(3) These extremely high loadings are achievable because of the capability of the system to carry and maintain mixed liquor volatile suspended solids (MLVSS) concentration values between 5,000 and 10,000 mg/L. As a result, a much lower volume (aeration period) is required than in the conventional activated sludge process.(4,5)

The hardware consists of a vertical subsurface reactor shaft between 90 and 250 m (300 to 800 ft) deep, with hydraulic mean residence times on the order of 60 minutes. Depending on the operating mixed liquor volatile suspended solids (MLVSS) concentration, the effluent from the reactor can be treated utilizing either the flotation or sedimentation process.

Based on a cost and energy analysis, no definitive conclusions could be drawn relative to cost or energy savings that can be realized by use of the Deep Shaft process. For the plant capacities used in the cost analysis (1,892 to 37,850 m^3/d; 0.5 to 10.0 mgd), the installed capital cost estimates for the Deep Shaft process were equivalent ($\pm$ 25%) to the conventional air activated sludge process.

The Deep Shaft process showed some savings in installed capital costs over the pure oxygen activated sludge system for all of the flow ranges for which the comparative analysis was prepared. when the cost comparison is based on present worth value, all three technologies are found to be equivalent. Based on this evaluation, no significant national impacts can be predicted for the Deep Shaft process.

A similar analysis was conducted for the energy requirements of the three technologies. Based on this analysis, it can be concluded that the unit energy requirements (kwh/1,000 m^3 of wastewater treated) are the highest for the Deep Shaft process when treating domestic wastewaters. The pure oxygen activated sludge process required the least unit energy for the 1,892 m^3/d (0.5 mgd) plant size because of the use of purchased liquid oxygen. For larger plant capacities (18,925 and 37,850 m^3/d), however, the pure oxygen process required the same unit energy as the conventional air activated sludge process. This was due to the requirement for additional energy for on-site oxygen generation.

Based on this analysis, it is evident that the Deep Shaft process benefits (cost and energy) can only be realized when the raw wastewater strength is greater than normal domestic wastewater. This is because the energy requirements for the Deep Shaft process treating domestic wastewaters are based on the requirement for maintaining liquid circulation velocities rather than on the basis of BOD_5 removal. When the raw wastewater BOD_5 concentration is high ($\geq$500 mg/L), the cost and energy savings are likely to be in favor of the Deep Shaft process.

This report was submitted in fulfillment of Contract No. 68-03-2775 by Roy F. Weston, Inc., under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period 7 May 1980 to 31 December 1980, and the work was completed as of 31 December 1980.

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ACKNOWLEDGMENTS

The cooperation of the U.S. EPA Municipal Environmental Research Laboratory Staff, Mr. John Smith, Mr. Robert P.G. Bowker, and Mr. Richard C. Brenner is greatfully acknowledged. We are particularly indebted to Mr. Bowker, who served as Project Officer during this effort, for his cooperation in assimilating review comments and in scheduling review meetings, as well as in assisting the project personnel in completing this assignment.

The technical assistance provided by Eco Technology personnel, especially Mr. Keith Day and Mr. Sanford, was extremely valuable in preparing the technology description of the various Deep Shaft development versions. Similarly, the staff members of the UNOX Corporation were helpful in providing project cost information for different capacity UNOX (Pure Oxygen) systems so that the technology comparison could be made on an equivalent basis.

SECTION 1

TECHNOLOGY DESCRIPTION

INTRODUCTION

One of the recent changes in Federal funding policy for municipal wastewater treatment facilities requires the analysis and evaluation of innovative and alternative technologies during the development of wastewater management alternatives. Section 201 (g)(5) of the Clean Water Act makes this requirement mandatory for planning studies initiated after September 30, 1978. The objectives of this requirement are:[1,2]

1. To incorporate more cost-effective and energy-efficient systems in publicly-owned treatment works (POTW's) than those utilizing traditional or conventional design practice.

2. To encourage innovative and alternative processes that provide for the reclamation and reuse of wastewater.

3. To encourage the utilization of recycling techniques, land treatment, and new and improved methods of joint municipal and industrial treatment.

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TECHNOLOGY DESCRIPTION

The Deep Shaft biological treatment process is essentially a high rate activated sludge process capable of operating at BOD_5 loading ratios (F/M) between 0.5 and 2.0 kg BOD_5/kg

MLVSS/day.[3] These extremely high loadings are achievable because of the capability of the system to carry and maintain mixed liquor volatile suspended solids (MLVSS) concentration values between 5,000 and 10,000 mg/L. As a result, a much lower volume (aeration period) is required than in the conventional activated sludge process.[4,5]

The process consists of a vertical subsurface reactor shaft between 90 and 250 m (300 to 800 ft) deep, with hydraulic mean residence times in the order of 60 minutes. The reactor is typically installed utilizing conventional drilling equipment using reverse mud circulation. The typical drilling equipment and the reverse mud circulation technique are illustrated in Figures 1 and 2. In general, carbon steel shafts are utilized for the exterior casing. The shafts are typically grouted with sulfate-resistant cement to allow isolation from the surrounding geological formation.

The reactor is divided basically into two sections, namely, a downcomer and a riser. In the initial reactor configuration, the raw wastewater and return sludge are introduced into the downcomer section of the reactor, and the mixed liquor is withdrawn from the riser section. Compressed air is introduced into both the downcomer and the riser sections to serve as a source of oxygen, as well as the driving force for fluid transport through the shaft. The air requirements and air injection depth are determined by taking into consideration the minimum liquid circulation velocity and BOD_5 removal requirements. In general, liquid circulation velocities between 0.9 and 1.5 m/s (3 and 5 ft/sec) are maintained within the Deep Shaft reactor. Depending on the operating mixed liquor volatile suspended solids (MLVSS) concentration, the effluent from the reactor can be treated utilizing either the flotation or sedimentation process.

In the case of domestic wastewater treatment, the raw influent wastewater generally undergoes preliminary treatment for the removal of large particles (screenings) and grit. Experience with the Deep Shaft process indicates that the process can operate successfully without primary clarification. Figure 3 shows the generalized block flow diagram for the treatment of domestic wastewaters using the Deep Shaft biological reactor. Figure 4 shows the general concept and flow pattern occurring within a Deep Shaft reactor.

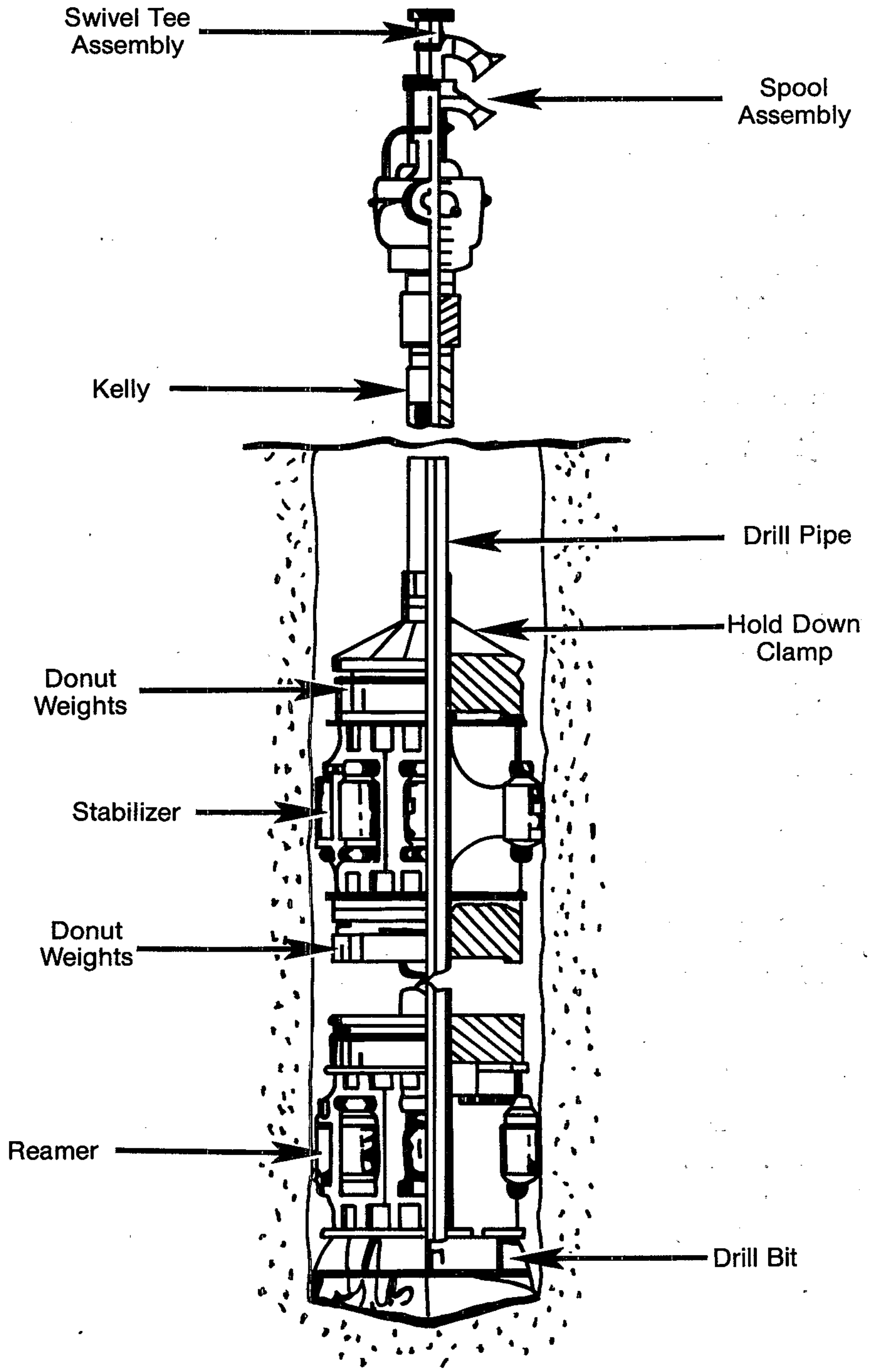


Figure 1. Big hole drilling assembly.

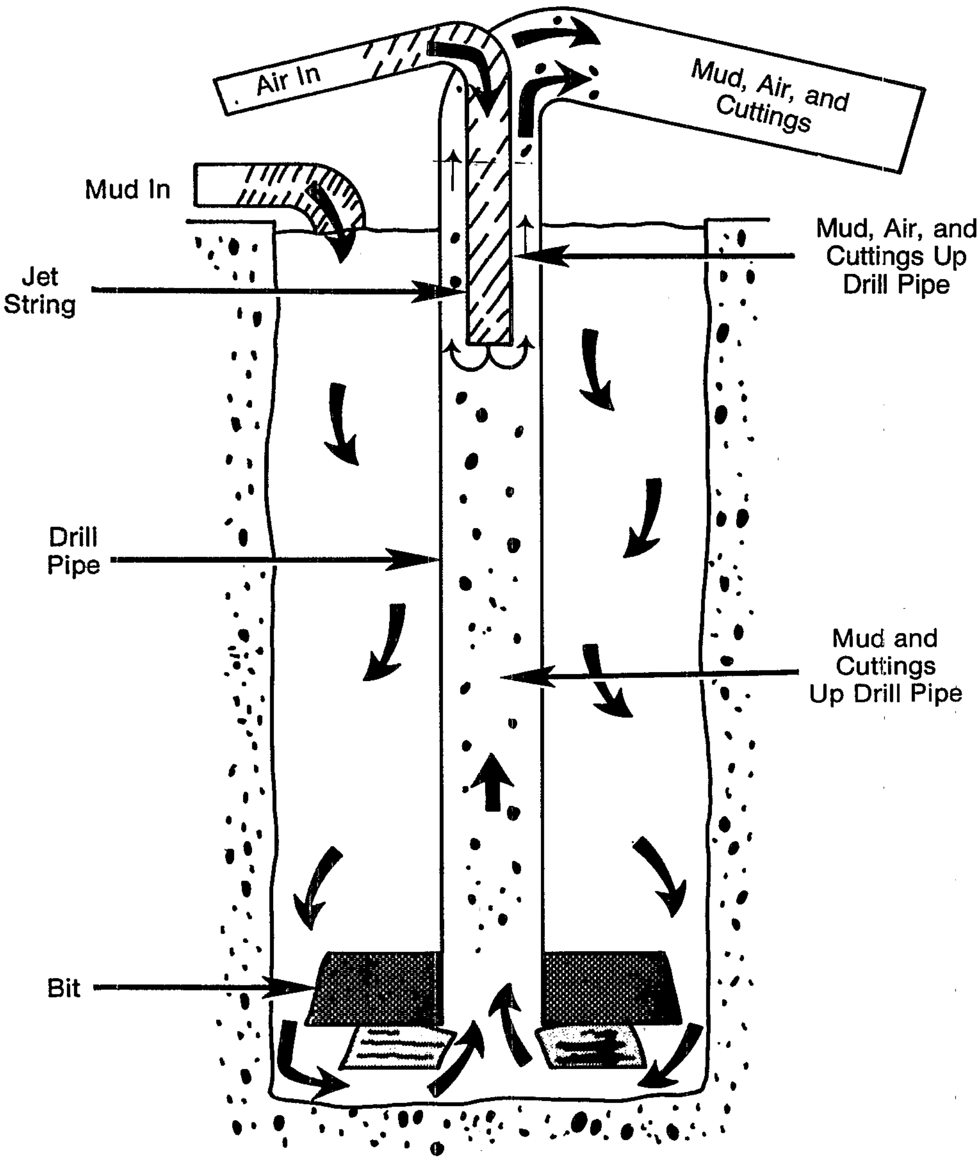


Figure 2. Reverse mud circulation with air assist.

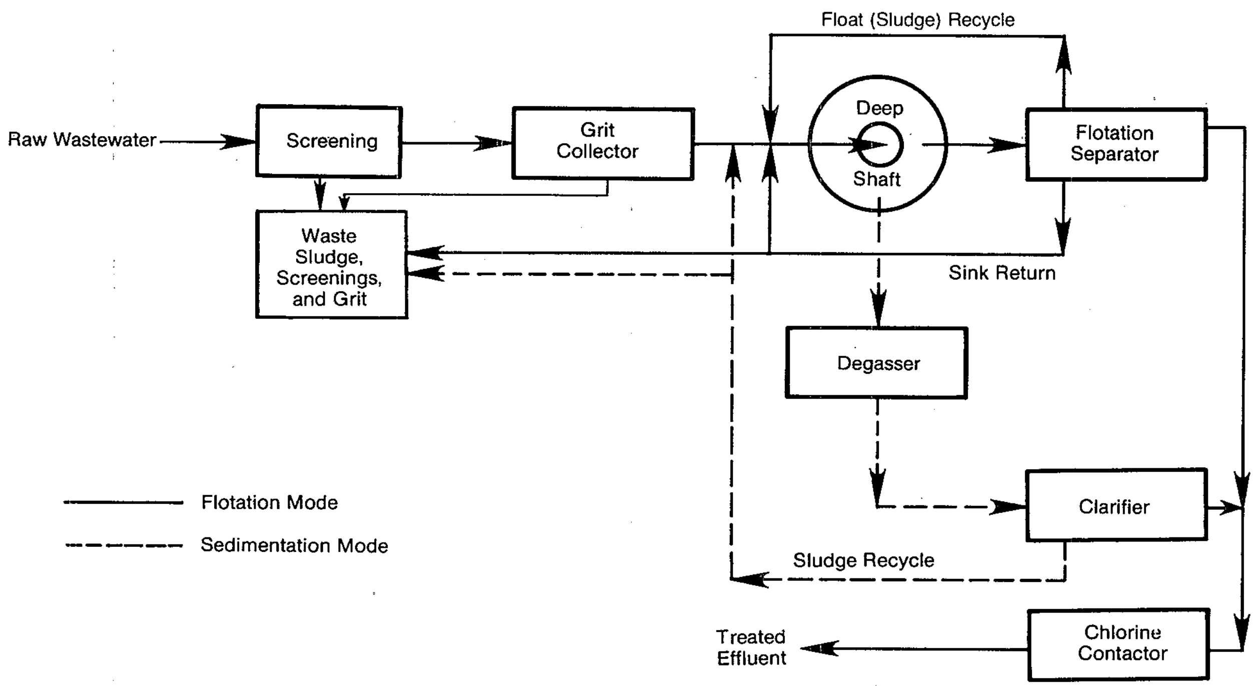


Figure 3. Deep Shaft biological treatment process flow schematic.

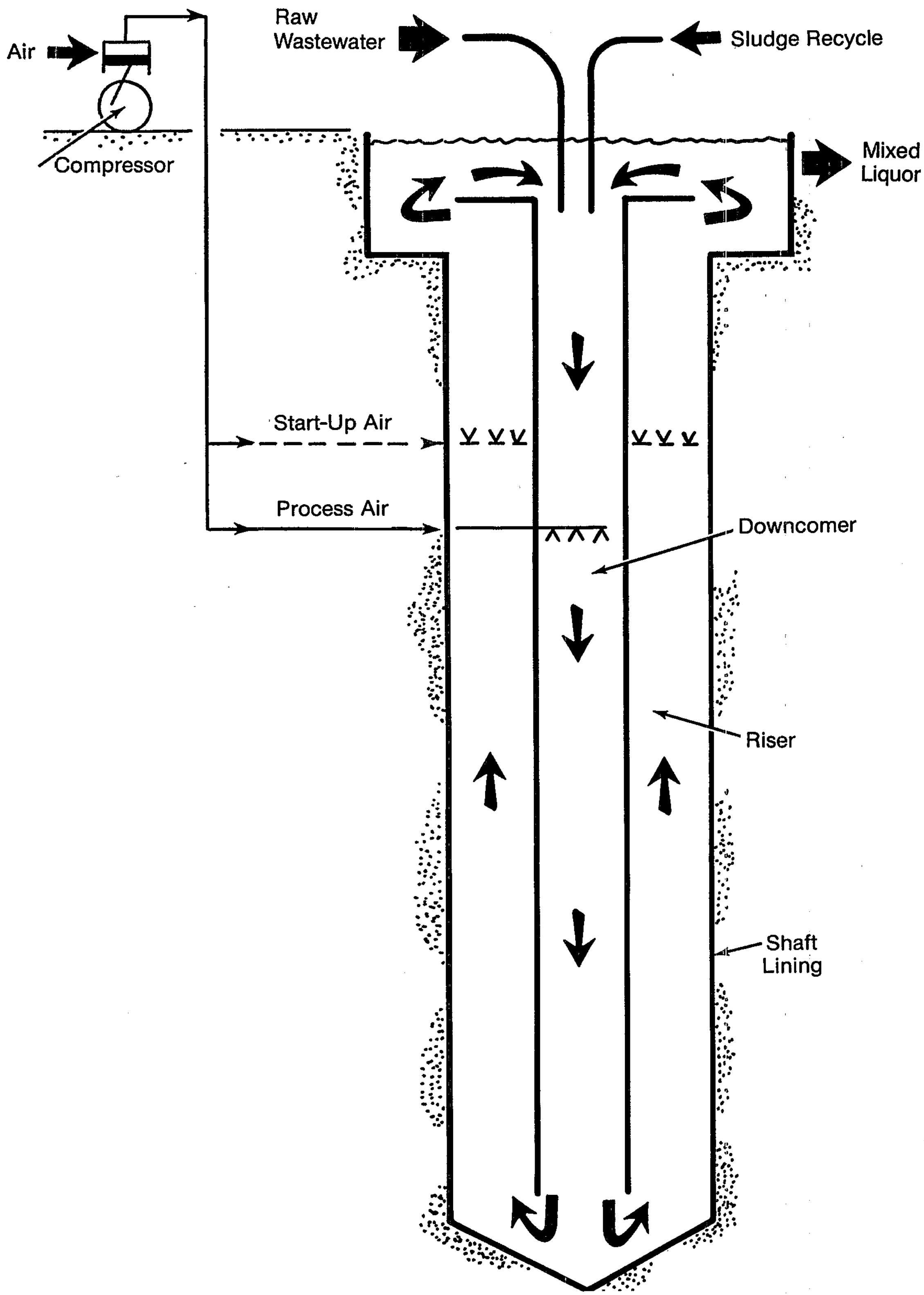


Figure 4. Mixed liquor flow pattern in Deep Shaft reactors.

SECTION 2

TECHNOLOGY DEVELOPMENT

DEVELOPMENT HISTORY

Deep Shaft biological treatment of wastewaters has its origin in the United Kingdom and was developed from research efforts for the synthesis and production of single cell protein using methanol as feedstock.[6] The process required the operation of the system with high bacterial density. In order to satisfy the extremely high requirements for dissolved oxygen, Imperial Chemical Industries Limited (ICI) adopted a pressure cycle aerobic fermentor (Deep Shaft reactor) in which the increased hydrostatic pressure between 90 to 250 m (300 to 800 ft) was utilized to increase oxygen transfer capabilities. The pressure cycle fermentor utilized air-lift principles in which the air for bio-chemical oxidation also provided the air for liquid circulation. An extension of this basic research and development work is the application of the process principles for wastewater treatment. Wastewater treatment application normally involves the operation of the Deep Shaft reactor with lower bacterial density, less biodegradable substrate (BOD_5), and a slower growth rate of microorganisms than in the single cell protein reactor. For these reasons, ICI, Ltd. modified the reactor configuration and increased the typical design depth of the reactor to achieve equivalent oxygen transfer efficiency and power economy.[7] In addition, ICI initiated several pilot and demonstration projects involving municipal and industrial wastewaters.

The ICI version of the Deep Shaft process consists of a deep subsurface well, a head tank, and a solids separation clarifier. The ICI Deep Shaft reactor configuration, along with the gas voidage and dissolved oxygen profiles, are presented in Figure 5. Gas voidage refers to the volume fraction of entrapped gas bubbles in the mixed liquor, and can be expressed as follows:

$$\text{Gas voidage} = \frac{\text{Volume of gas bubbles}}{(\text{Volume of gas bubbles + volume of liquid})} \quad (1)$$

The gas voidage difference between the riser and the downcomer sections of the Deep Shaft reactor is utilized to initiate and maintain liquid circulation within the reactor.

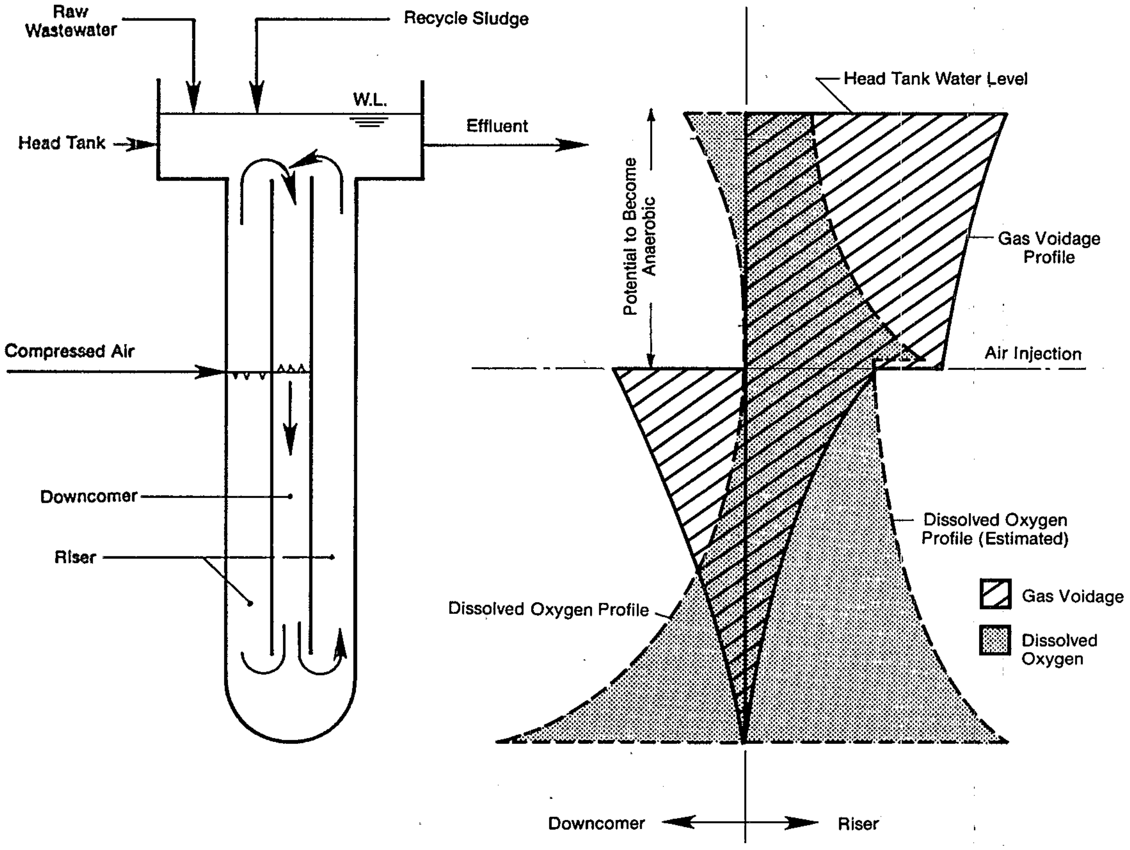


Figure 5. ICI-Deep Shaft reactor configuration along with gas voidage and dissolved oxygen profile.

The ICI Deep Shaft reactor is divided into two concentric sections; one is called the downcomer and the other the riser. Raw wastewater and recycle sludge are introduced into an open head tank from which the mixed liquor flows down the downcomer and upward through the annular riser section to the head tank. Mixed liquor is also withdrawn from the head tank for solids separation and to provide for recycle sludge.

Based on these operating principles, a pilot plant was started by ICI in Billingham, England during 1974. The pilot plant had a design capacity of approximately 363 m^3/day (96,000 gpd). A 39 cm (15.25 in.) diameter shaft, 130 m (426 ft) deep provided the outside shell for the Deep Shaft process. During the initial operation of the pilot plant, the solids separation process consisted of a dissolved air flotation unit followed by a mechanical degasser and clarification unit. The flotation separator was included in the process to make use of the potentially available dissolved gases present in the Deep Shaft mixed liquor. Subsequent experience with the Deep Shaft system indicated that the flotation unit and the mechanical degasser can be replaced with a vacuum degasser prior to clarification. Further testing using the clarification mode indicated that the process is capable of producing better than secondary quality effluent (BOD_5 = 15 mg/L; SS = 18 mg/L) when operating at mixed liquor suspended solids concentration (MLSS) values between 2,000 and 6,000 mg/L.[7,8,9]

In summary, the process development and successful demonstration at Billingham, England have created sufficient interest in Europe, North America, and Japan to warrant extensive marketing efforts. Accordingly, ICI has extended process licenses to Canadian Industries Limited (CIL) of Canada for carrying out the marketing efforts in North America. Eco Technology (Eco), a division of CIL, assumed this responsibility in mid-1975 and has contributed significantly to the current exposure and development of this technology. The following subsection describes the status of development in North America.

DEVELOPMENT STATUS

Eco Technology, a subsidiary of CIL, recognized that the Deep Shaft reactor volume can be significantly reduced if the overall system can be designed to operate with high mixed liquor suspended solids ($\geq$ 6,000 mg/L). Eco Technology also realized that the limiting constraint for operating the system with high mixed liquor suspended solids is the gravity separation of the mixed liquor solids leaving the Deep Shaft reactor. The use of a gravity separation process unit (e.g., clarifier) has generally been limited to mixed liquor solids concentration values below 6,000 mg/L.[10,11] This is due to the recommended design criteria for solids flux through the gravity separation unit. Figure 6 shows the relationship between MLSS, hydraulic overflow rate, and solids flux rate for conventional clarification. Based on this consideration, Eco's development work was initially directed toward incorporating the flotation separator with the Deep Shaft process. This process system has become known as Eco-I, the first generation system introduced in North America.

Eco-I Description

The Eco-I Deep Shaft treatment system essentially consisted of a reactor and a flotation separator. The configuration retained for Eco-I was similar to the ICI model, where the raw wastewater and return sludge are both introduced to the head tank and flow through the downcomer and riser sections prior to leaving the reactor. The velocity in the shaft is maintained between 0.9 and 1.5 m/s (3 to 5 ft/s) to prevent deposition of solids within the shaft. The head tank for Eco-I was designed large enough to disengage coarse air bubbles released during upward flow in the reactor. The mixed liquor from the head tank is then treated in a flotation cell. Figure 7 shows the process flow diagram for the first pilot-scale plant installed at Paris, Ontario utilizing the Eco-I design.(7) The Paris, Ontario pilot plant was constructed with a 39-cm (15.25 in.) shaft which is 155 m (508 ft) deep.

To initiate flow through the reactor, air from a 690-kPa (100 psi) compressor is first introduced to the riser section. Upon initiation of flow, the air flow to the riser section is gradually reduced while increasing air supply to the downcomer. Under normal operating conditions, the air distribution between the downcomer and riser sections is maintained at 67 and 33 percent, respectively. The incorporation of the dissolved air flotation process in the Eco-I design is significant because:

1. Flotation solids are generally of higher concentra- ($\geq$ 4%) than underflow solids from gravity sedimentation units ($\leq$1.5%).

2. Mixed liquor from the Deep Shaft reactor can be introduced directly into the flotation cells without the requirement for a separate air dissolution system.

3. Single source of air supply provides the required dissolved oxygen and the driving force for both mixed liquor circulation and solids separation in the flotation cell.

4. Increased concentration of float solids significantly reduces the size requirements for waste sludge handling, treatment, and disposal equipment.

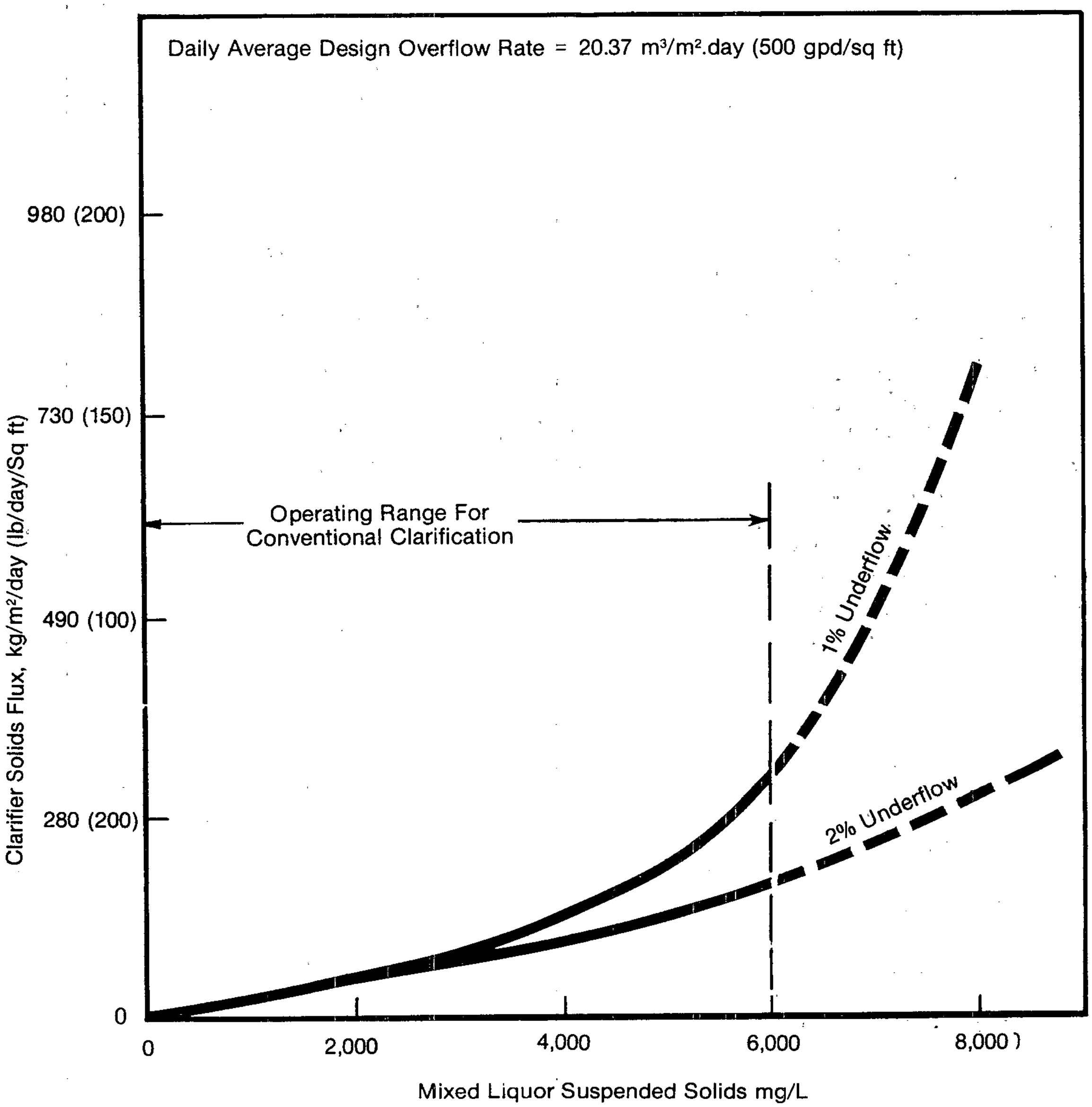


Figure 6. Relationship between mixed liquor suspended solids concentration and solids flux.

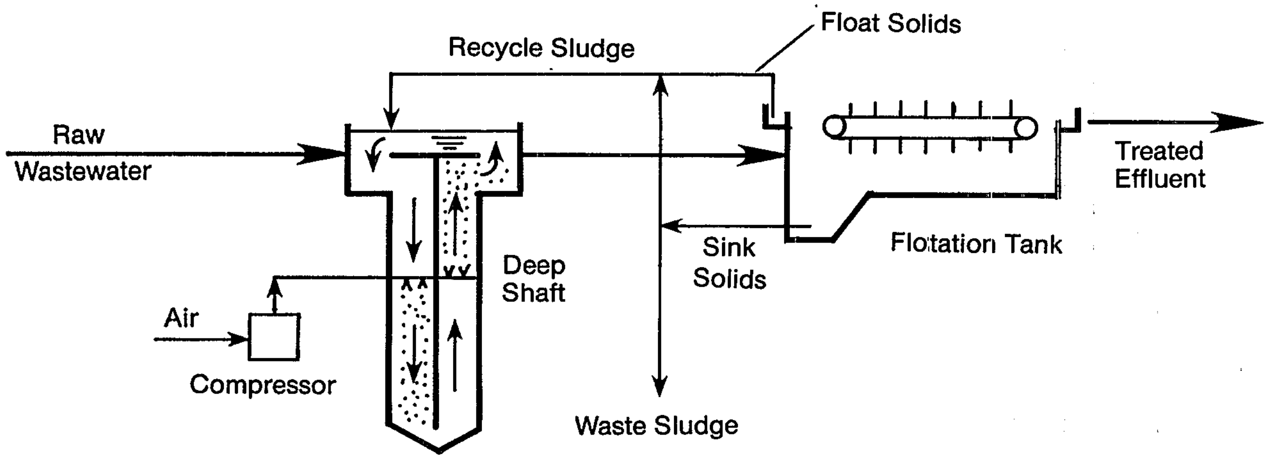


Figure 7. Generalized process flow diagram -- Eco-I design.

Even though the Eco-1 Deep Shaft process was successful in treating both municipal and industrial wastewater, the Eco-I operation had the following deficiencies:

1. Potential exists for the development of an anaerobic environment in the downcomer section between the air injection point, approximately 50 m (160 ft) below the water surface and the head tank where the raw wastewater and return sludge flows are introduced (Figure 7).

2. Since the raw wastewater injection and mixed liquor withdrawal are located within the head tank, there is always the possibility short-circuiting of the influent flow.

3. Eco-I operation requires air injection to both the downcomer and the riser. The air flow rates between the two sections must be properly adjusted to maintain the proper gas voidage ratio, and, therefore, the flow pattern. In the absence of proper air flow distribution between the two sections, hydraulic flow reversal can occur, thereby increasing the possibility for short-circuiting of the influent flow.

4. Eco-I Deep Shaft reactor biology is subject to varying oxygen tension and waste strength.

5. Eco-I design does not capitalize on the full potential of dissolved gases available inside the reactor. As the mixed liquor flows through the riser section, it undergoes depressurization; therefore most of the dissolved gases are released through the open head tank which is maintained at atmospheric pressure.

Eco-II Description

The information developed during Eco-I design and pilot plant experiences gained with the Paris, Ontario operation, plus the full-scale experience with the Emlichheim, West Germany operation have paved the way for improving the Eco-I design and the resultant development of the second generation Eco-II design.[10,11]

The Eco-II design basically addressed the shortcomings of the Eco-I design with respect to the location of influent and effluent piping and the maintenance of a more stable hydraulic flow regime. This was accomplished by incorporating a multichannel configuration in the shaft design. Figure 8 shows the simplified process flow schematic utilizing the Eco-II reactor.

In the Eco-II design, influent raw wastewater, together with the return sludge and overflow from a newly-provided foam oxidation tank, is introduced to the Deep Shaft riser section at a depth close to the air injection point (25 to 50 m deep). The riser section of the Eco-II reactor is compartmentalized into four sections, as follows (see Figure 8):

1. Primary riser (R_1).
2. Secondary riser (R_2).
3. Secondary downcomer (D_2).
4. U-tube riser (D_2R_1).

The combined influent stream (raw wastewater plus return sludge) is introduced into the secondary downcomer (D_2) and then driven through the U-tube riser (D_2R_1) to the primary riser (R_1) section of the Deep Shaft reactor. When the influent stream exits from the U-tube riser (D_2R_1), it is combined with mixed liquor flowing through the primary riser (R_1). The wastewater then flows through the primary downcomer (D_1) and then the flow is split between the primary (R_1) and secondary (R_2) risers. A portion of mixed liquor is withdrawn through the secondary riser (R_2) for solids separation and effluent discharge. The secondary riser (R_2) is located at a

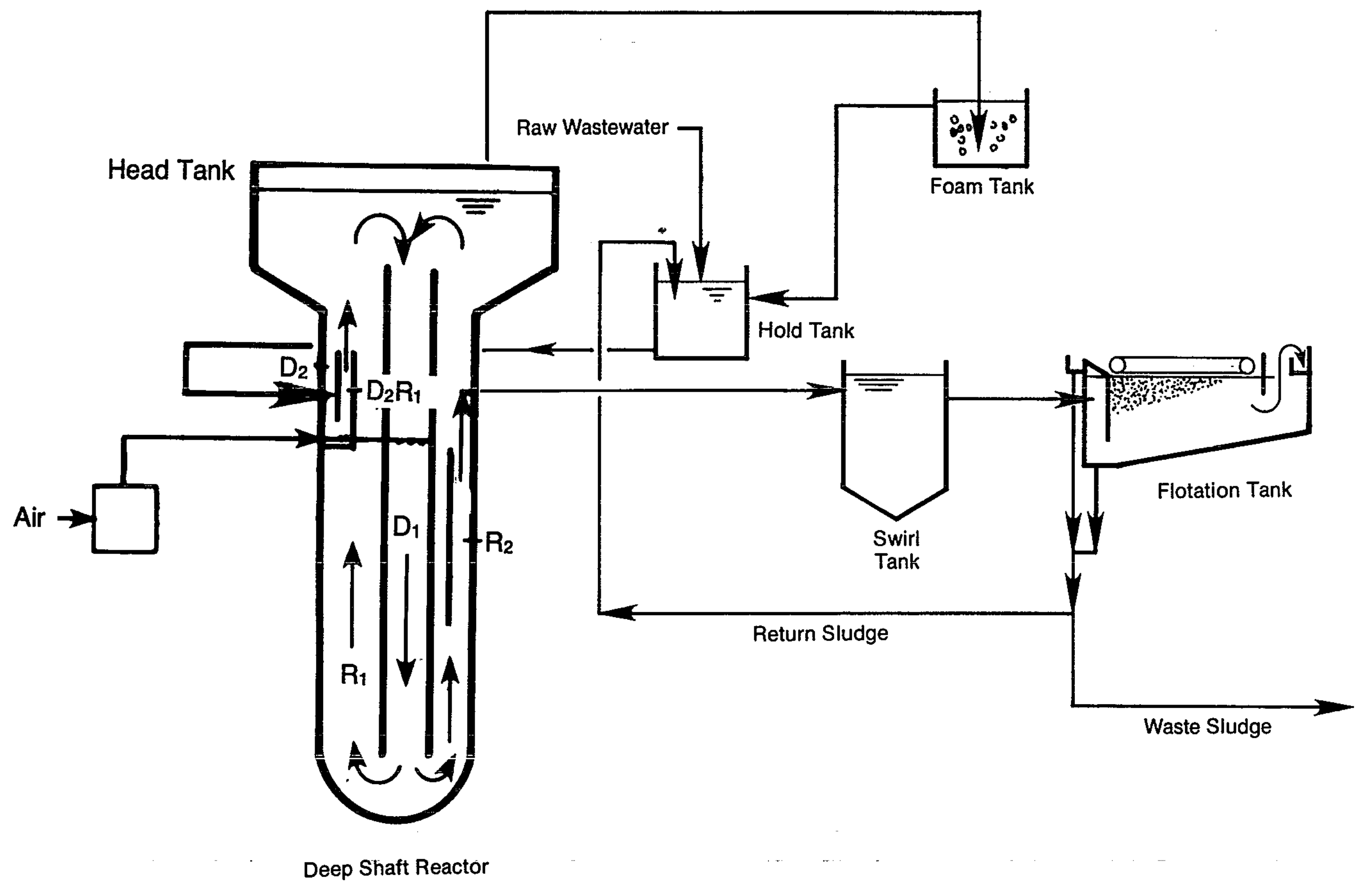


Figure 8. Deep Shaft process flow schematic -- Eco II design.

lower elevation than the U-tube riser section (D_2R_1) to eliminate short-circuiting of influent to the reactor. With this change in influent injection and effluent withdrawal locations, the air distribution between the downcomer and riser sections of the shaft is also revised to inject 67% of the total air requirement to the U-tube riser (D_2R_1) and 33% to the primary downcomer (D_1). As a result, the possibility for flow reversal within the shaft is eliminated and the hydraulic integrity of the shaft preserved.

The mixed liquor withdrawn from the Deep Shaft is then passed through a swirl tank for the removal of coarse air bubbles prior to solids separation in a flotation-clarifier. The head tank design for the Eco-II reactor is also modified and operates as a closed pressure vessel. The head tank is designed to operate under 20 to 55 kPa (3 to 8 psi) pressure, and the pressure is controlled by a submerged outlet pipe for the off gases. The off-gas submergence is provided in what is known as a "foam tank" which is used to collapse and collect any foam carried with the off-gas mixture. The foam tank is also used to oxidize surfactants and to minimize foaming within the Deep Shaft reactor.[9,12]

Improvements in the Eco-II design include the elimination of the potential anaerobic zone along the downcomer section of the Eco-I design. This was accomplished by relocating the influent flow to the reactor near the air diffusers in the riser section. The riser air is more efficiently utilized in the Eco-II design than in Eco-I design in which the riser air was primarily provided for maintaining the proper gas voidage ratio between the downcomer and the riser. As a result, the total air requirements for the Eco-II design are only 80 percent of those required for the Eco-I design. Figure 9 shows the gas voidage and dissolved oxygen profile within the Eco-II Deep Shaft reactor.

Eco-III Description

Based on the experience gained with the operation of both Eco-I and Eco-II systems, a third generation equipment configuration was developed by Eco Technology, hereinafter referred to as Eco-III. The second generation Deep Shaft reactor configuration (Eco-II) optimized the biological profile inside the reactor and stabilized the hydraulic flow pattern. The air supply requirements for the Eco-II reactor, however, were determined predominantly to maintain liquid circulation at peak flow conditions. One of the improvements in the Eco-II reactor design involves the more efficient use of the aeration energy by controlling the air flow rate to match influent wastewater flow.

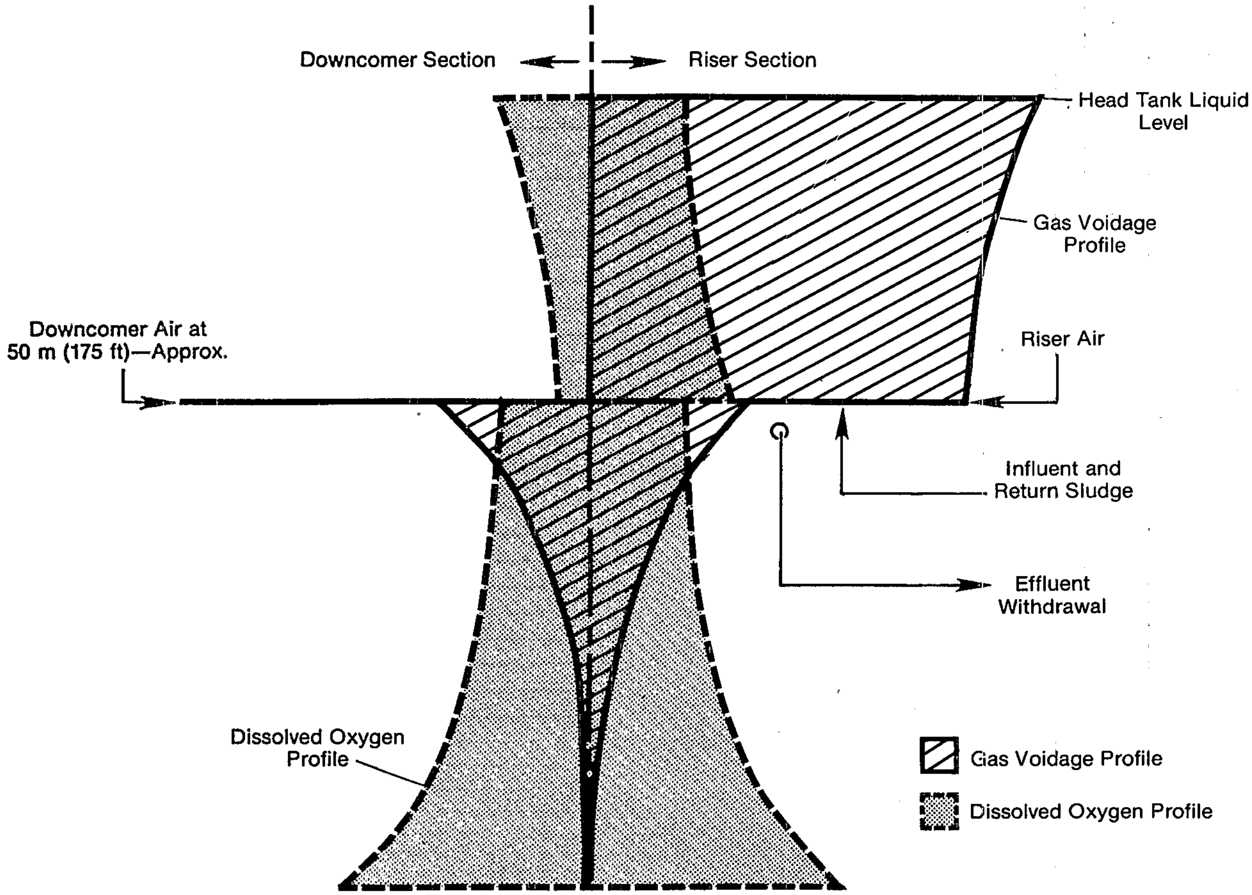


Figure 9. Gas voidage and D.O. profile -- Eco-II reactor.

The Eco-III model has the same multichannel configuration as Eco-II; however, the reactor configuration (inside the shaft) has been modified to attain approximately equal head loss (friction loss) in the primary downcomer and riser sections. The major improvements in the Eco-III design involve: the integration of the foam oxidation tank and head tank into a single unit, the elimination of the swirl tank and extensive process control instrumentation, and design improvements in the flotation unit. These design features are described briefly in the following paragraphs. Figure 10 shows the shaft configuration and channel geometry for the Eco-III reactor.

Figure 11 shows the isometric view of the head tank arrangement for the Eco-III reactor. The head tank is submerged within the foam tank, and is equipped with two vent passages for the effluent gas mixture from the Deep Shaft reactor. The two vent passages have different levels of submergence in the foam tank, thereby providing for two operating pressure stages, P_1 and P_2, inside the head tank. Figures 12 and 13 show a simplified schematic of the head tank and the vent gas control system. Referring to Figure 12, normal flow (design) conditions, the operating liquid level inside the head tank will be maintained at level L_1 with a corresponding head tank pressure at P_1. The total hydraulic flow through the Deep Shaft reactor at "average" design conditions is Q_{T1}. The flow components to the reactor consist of the raw waste influent Q_i, recycle float sludge Q_F, settled sink sludge return from the flotation tank Q_S, and the foam tank overflow, and cumulatively represent the design flow for the reactor. In general, any deviations in influent flow rate (Q_i) will be balanced with variations in return sink flow rate (Q_S) from the flotation unit. The gravity return of settled sink sludge from the flotation unit to the holding tank allows automatic control of the sink sludge flow in proportion to the hydraulic head difference between the flotation unit and the holding tank.

In summary, the sink flow rate Q_S will vary inversely proportional to the raw waste flow rate (Q_i) so that the sum of these two flows (Q_i+Q_S) will remain at approximately a steady rate. Similarly, during this operating mode (stage pressure P_1), the float skimming mechanism will be operating at speed N_1, providing a steady return sludge flow rate (Q_F). As a result, the Deep Shaft reactor and the flotation separator unit will be operating under constant hydraulic and solids loading, respectively. The air supply requirements will also be maintained at a steady rate to achieve desired liquid circulation velocities inside the reactor. Figure 14 shows the typical hydraulic profile and the flow routing for the Eco-III reactor system.

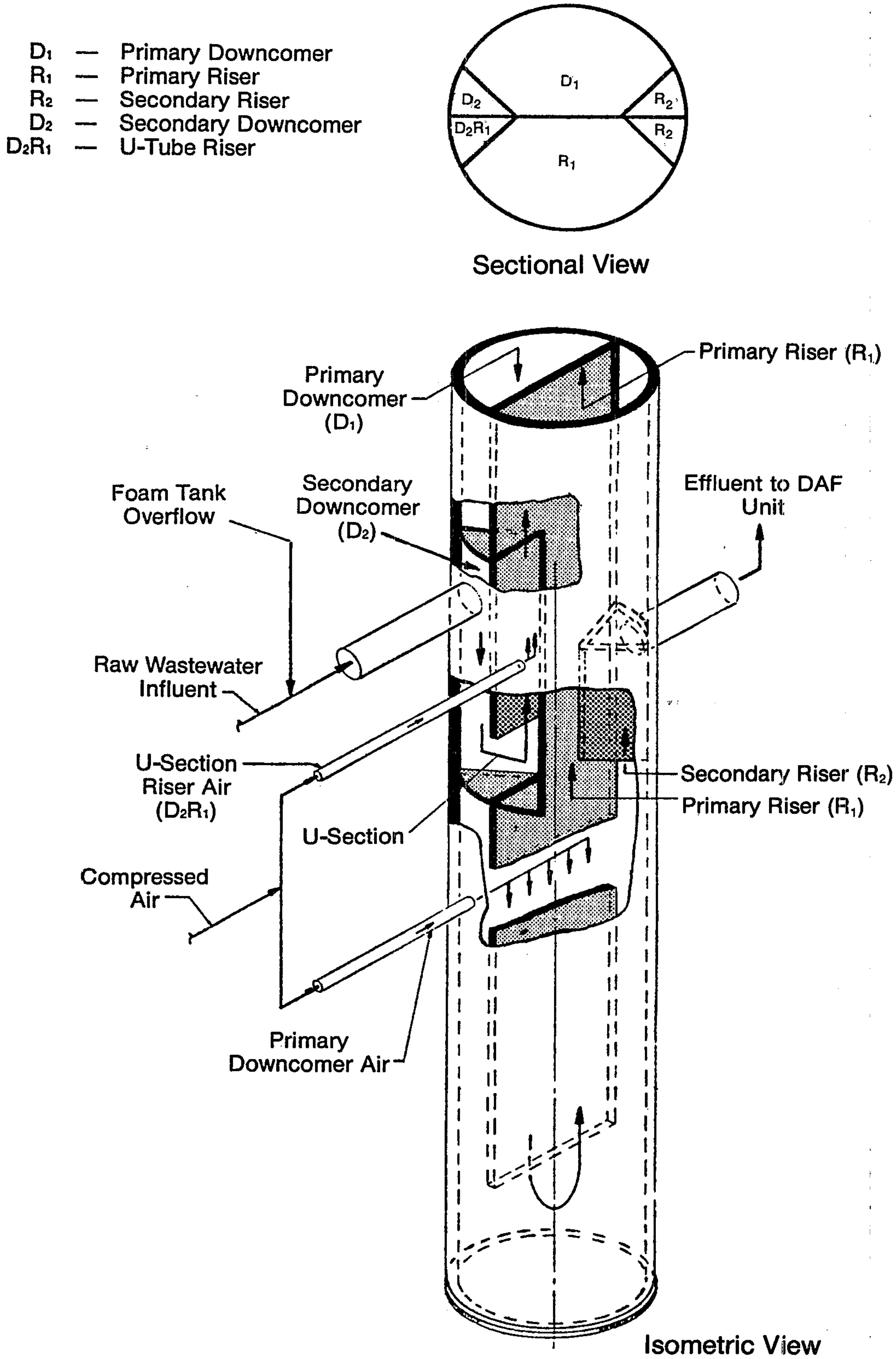


Figure 10. Shaft configuration and channel geometry detail for Eco-III Deep Shaft reactor.

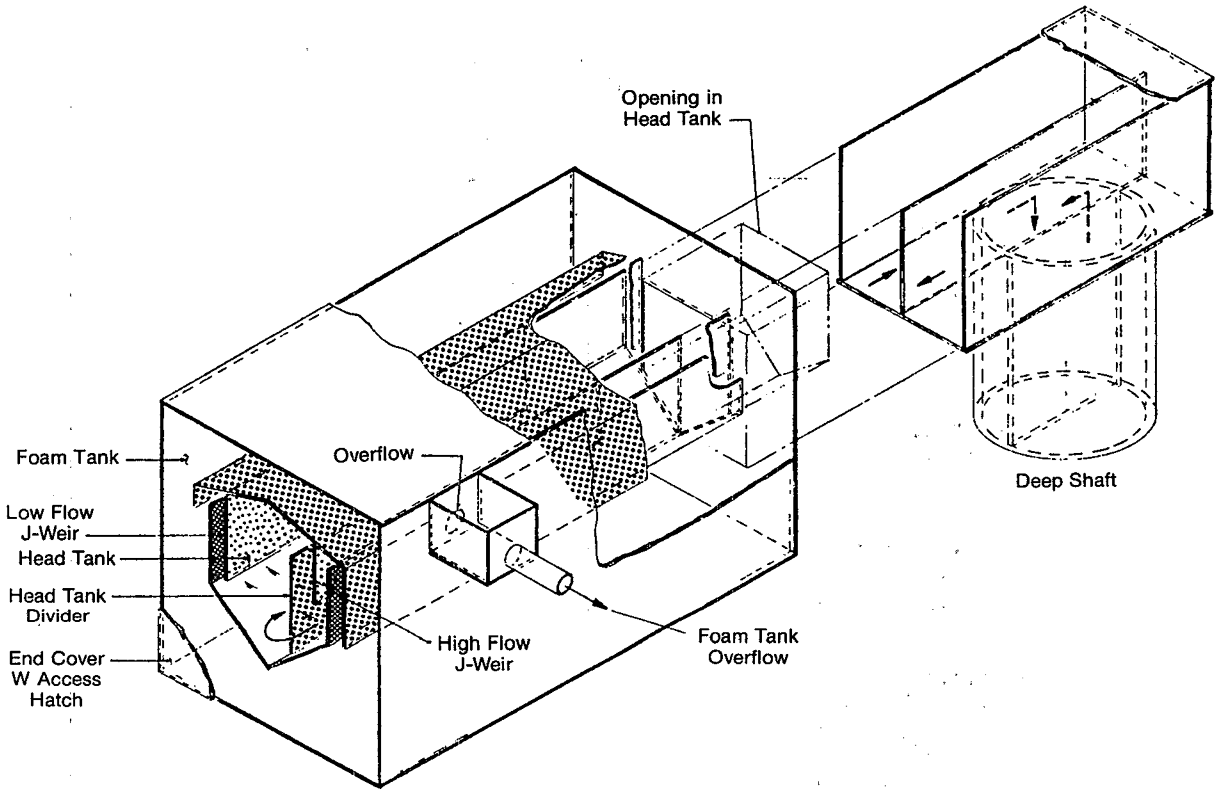


Figure 11. Head tank arrangement - Eco III reactor.

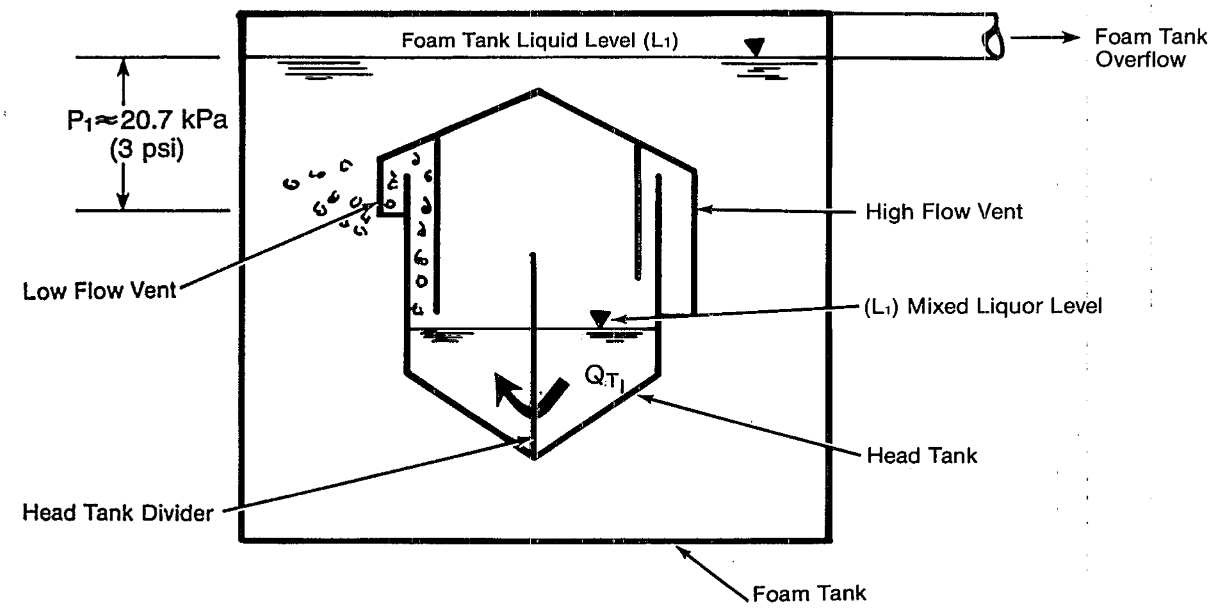


Figure 12. Head tank operating characteristics - normal flow (design) conditions (stage 1).

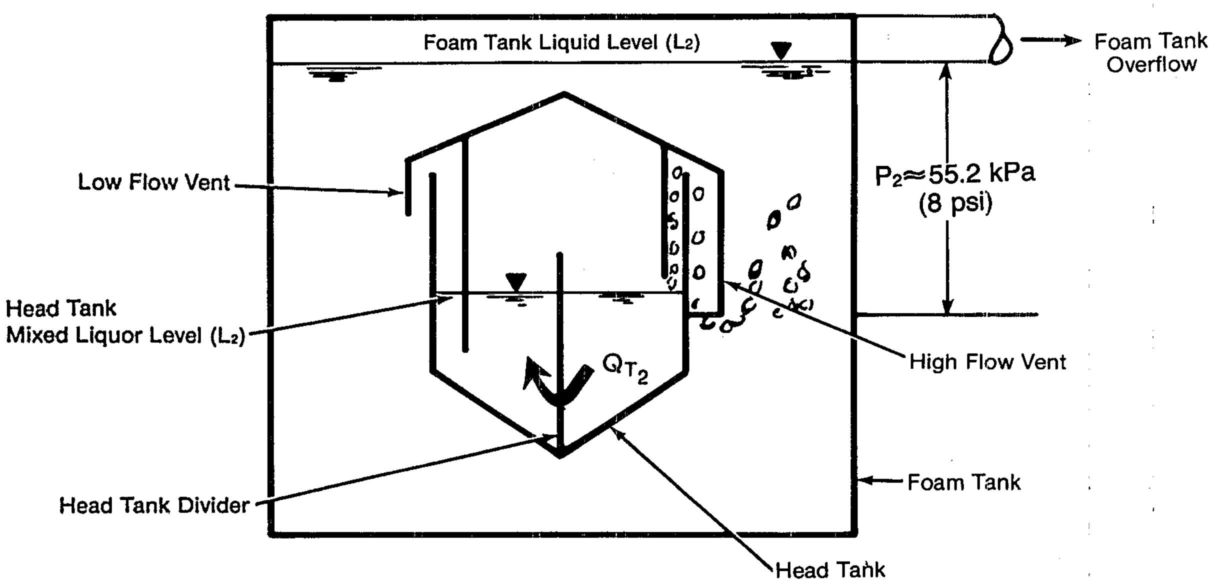


Figure 13. Head tank operating characteristics - high flow (design) conditions (stage 2).

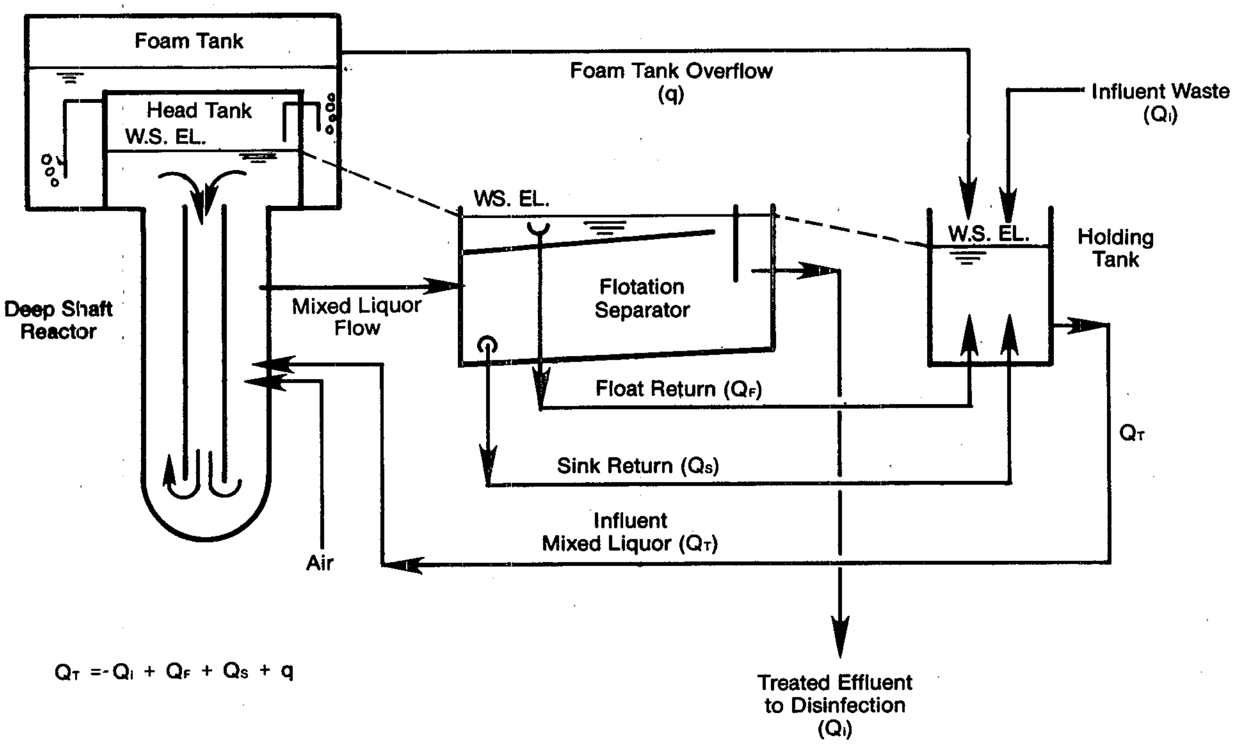


Figure 14. Hydraulic profile - Eco-III reactor.

When the raw wastewater flow rate (Q_i) exceeds the normal design conditions ($Q_i > Q_{T1}$), the liquid level inside the head tank rises to maintain flow through the reactor. (See Figures 12 and 13.) As the liquid level rises above L_1, the low pressure gas vent becomes closed and the head tank pressure will reach the second operating stage (P_2). As a result, the hydraulic throughput capacity for the reactor can be increased to a new level (Q_{T2}). A liquid level or pressure sensor inside the head tank will actuate and increase air supply to accommodate the increased hydraulic flow or to provide additional oxygen requirements. The liquid level or pressure control is the only process control instrumentation required for the Eco-III reactor operation. The output signal from the liquid level control can also be interconnected with the float skimmer drive mechanism to attain increased recycle float sludge (Q_{F2}).

The Eco-III design recommends a two-speed drive for the float skimmer in order to maintain proper mixed liquor suspended and volatile suspended solids concentrations in the reactor. In general, this design feature allows the system to operate under defined stages of hydraulic flow (Q_T) and solids flux, and, therefore, the system is free from performance variations that can be associated with hourly variations in raw wastewater flow rate. In addition, the air supply and the energy consumption can be tuned with the influent hydraulic flow pattern to the treatment system.

The other design modification in the Eco-III reactor system involves the flotation separator unit. The flotation separator for the Eco-III reactor system is equipped with a 'J' baffle and a specially designed float sludge skimming ramp. The 'J' shaped baffle serves as an impinging barrier for the mixed liquor feed and helps to separate and release the coarse air bubbles from the feed stream. As a result, the swirl tank requirement has been eliminated and the mixed liquor from the Deep Shaft reactor can be directly fed to the flotation separator. Similarly, the float sludge skimming ramp serves to circulate the mixed liquor feed stream around the 'J' baffle and is believed to promote flocculation of the mixed liquor suspended solids. Improvements to the flotation tank design are shown schematically in Figure 15.

Table 1 summarizes the various features and improvements in the design of the three model versions of the Deep Shaft reactor system. An Eco-III Deep Shaft treatment system is currently being installed for the City of Portage Le Prairie in Canada. The status of development since the original ICI reactor was developed in 1974 and the performance of Deep Shaft reactors are summarized in Tables 2 and 3.

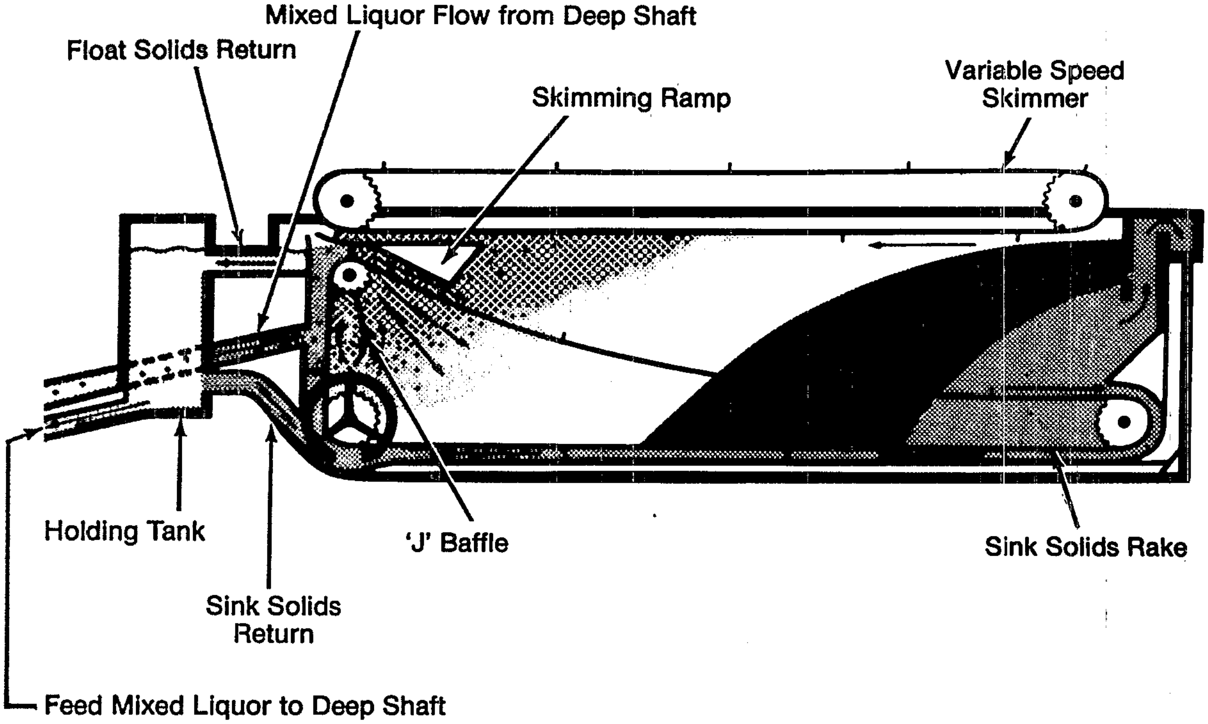


Figure 15. Flotation tank modifications -- Eco-III reactor and mixed liquor feed to Deep Shaft.

TABLE 1. COMPARISON BETWEEN THREE MODEL VERSIONS OF THE DEEP SHAFT REACTOR SYSTEM

Process/Equipment Features	Eco-I	Eco-II	Eco-III
1. Head tank pressure	Atmospheric.	Single operating pressure between 20.7-55.2 kPa (3-8 psi).	Two (2) distinct stages of operating pressure; between 20.7-55.2 kPa (3-8 psi).
2. Shaft configuration	Two channels consisting of a downcomer and a riser.	Multichannel configuration to include secondary riser and secondary downcomer.	Improved multichannel configuration to approach equal head loss (friction) between the downcomer and the riser sections.
3. Dissolved air flotation tank	Includes swirl tank for the release of coarse air bubbles.	Direct feed from Deep Shaft to DAF unit; incorporates a bottom scraper.	Improved DAF unit design; includes a 'J' baffle and a float skimming ramp.
4. Foam oxidation tank	None	Separate foam oxidation tank to biologically stabilize foaming agents and to reduce foam in head tank.	Foam oxidation tank installed within head tank; serves dual function: to maintain head tank pressure stages and to stabilize foaming agents.
5. Influent and return sludge introduction	To head tank.	To secondary downcomer (D_2) 50 m (150 ft) below liquid level.	To secondary downcomer (D_2) 50 m (150 ft) below liquid level.
6. Effluent withdrawal	From head tank.	From secondary riser (R_2); 50 m (150 ft) below head tank liquid level.	From secondary riser (R_2); 50 m (150 ft) below head tank liquid level.
7. Air injection	To riser and downcomer.	To primary downcomer (D_1) and U-section riser (D_2R_1).	To primary downcomer (D_1) and U-section riser (D_2R_1).
8. Air supply distribution	67% of total air supply to the downcomer; 33% to the riser.	33% of total air supply to the primary downcomer (D_1); 67% to the U-section riser (D_2R_1).	33% of total air supply to the primary downcomer (D_1); 67% to the U-section riser (D_2R_1).

TABLE 2. DEEP SHAFT DEVELOPMENT AND EXPERIENCE SUMMARY

Location	Plant Size	Type of Wastewater	Deep Shaft Model and Year Commissioned	Scale (Purpose)	Reference
1. Billingham, United Kingdom	363 m^3/d (96,000 gpd)	Domestic and industrial	ICI; 1974	Demonstration	(5) (18)
2. Marsh Farm Sewage Works, Tilbury, Essex, United Kingdom	6,620 m^3/d (1.75 mgd)	Domestic and industrial	ICI; 1978	Full scale	(21) (28)
3. Emlichheim, West Germany	1,060 m^3/d (0.28 mgd)	Industrial	ICI; 1975	Full scale	(8)
4. Kimberly Clark Co., Prudhoe, United Kingdom	21,600 m^3/d (5.71 mgd)	Industrial	ICI; NA	Full scale	(8)
5. ICI -- Agricultural Div. United Kingdom	1,575 m^3/d (0.42 mgd)	Industrial	ICI; NA	Full scale	(8)
6. Leer, West Germany	32,500 m^3/d (8.58 mgd)	Domestic and industrial	ICI; NA	Full scale	(8)
7. Paris, Ontario Canada	454 m^3/d (0.12 mgd)	Domestic	Eco-I; 1976	Demonstration	(5) (13)
8. Paris, Ontario Canada	6,246 m^3/d (1.65 mgd)	Domestic	Eco-III; 1980	Full scale	(31)
9. Molson Breweries Barrie, Ontario, Canada	125 m^3/d (33,000 gpd)	Industrial	Eco-I; 1976	Pilot scale	(24)
10. Molson Breweries Barrie, Ontario, Canada	2,091 m^3/d (0.55 mgd)	Industrial	Eco-II; 1980	Full scale	(30)
11. Bon Conseil, Quebec, Canada	2.7 m^3/d (750 gpd)	Industrial	Eco-I; 1977	Pilot scale	(12) (24)
12. City of Ithaca, New York	757 m^3/d (0.2 mgd)	Mostly domestic	Eco-II; 1979	Demonstration	(19)
13. City of Virden, Manitoba, Canada	2,400 m^3/d (0.63 mgd)	Domestic	Eco-I; 1979	Full scale	(17)
14. City of Portage La Prairie, Manitoba, Canada	13,615 m^3/d (3.6 mgd)	Domestic and industrial	Eco-III; 1981	Full scale	(25) (26) (27)

NA = Not available

TABLE 3. DESIGN AND PERFORMANCE DATA FOR DEEP SHAFT FACILITIES

Location	Design Capacity	Shaft Dimensions	Residence Time	F/M, BOD_5/MLVSS kg/day	Effluent Quality BOD_5 mg/L	Effluent Quality SS mg/L	Float Solids Concentrations
1. Billingham, United Kingdom	363 m^3/d (96,000 gpd)	40.6 cm (16 in) dia. 130 m (426 ft) deep	70 min	0.8	6-35	7-39	NA
2. Marsh Farm Sewage Works Tilbury, Essex, United Kingdom	6,620 m^3/d (1.75 mgd)	2 m (78 in) dia. 130 m (426 ft) deep	ND	ND	ND		ND
3. Emlichheim, West Germany	1,060 m^3/d (0.28 mgd)	1.1 m (3.6 ft) dia. 100 m (330 ft) deep	120 min	1.5	60-100	290	ND
4. Paris, Ontario, Canada	454 m^3/d (0.12 mgd)	39 cm (15.25 in) dia. 155 m (508 ft) deep	35-55 min	0.4-2.0	7-96	10-121	6-9%
5. Paris, Ontario, Canada	6,246 m^3/d (1.65 mgd)	0.81-0.91 m (32-36 in) dia. 122 m (400 ft) deep	~55 min[1]	1.35[1]	<15[1]	<15[1]	ND
6. Molson Breweries, Barrie, Ontario	125 m^3/d (33,000 gpd)	44 cm (18 in) dia. 155 m (508 ft) deep	288 min	2.6-5.0	43-109	47-257	ND
7. Molson Breweries, Barrie, Ontario	2,091 m^3/d (0.55 mgd)	21.26 cm (54 in) dia. 152.4 m (500 ft) deep	300 min	0.86-1.3	50	67	3.5%
8. Bon Conseil, Quebec, Canada	4 m^3/d (1,300 gpd)	6.75 cm (2.66 in) dia. 150 m (492 ft) deep	330 min	1.5-4	60-125	138-206	ND
9. City of Ithaca, New York	757 m^3/d (0.2 mgd)	43.8 cm (17.25 in) dia. 136 m (446 ft) deep	39 min	0.74	30	30	8-8.5%
10. City of Virden, Manitoba, Canada	2,400 m^3/d (0.63 mgd)	76.2 cm (30 in) dia. 153 m (500 ft) deep	41 min	1.06	30	30	ND
11. City of Portage La Prairie, Manitoba, Canada	13,615 m^3/d (3.6 mgd)	1.32 m (52 in) dia. 198 m (650 ft) deep	30 min[1]	1.53[1]	30[1]	30[1]	ND

ND = No data
[1]Represents design criteria; not from actual operation.

SECTION 3

TECHNOLOGY EVALUATION

PROCESS THEORY

Deep Shaft biological treatment is a high-rate activated sludge process in which a very high mixed liquor microbial population can be maintained to achieve proportionally increased organic removal rates. It is well known that biochemical oxidation of organic compounds is basically controlled by the following process parameters (15,16):

1. Concentration of organics (BOD).
2. Concentration of active biological solids (MLVSS).
3. Relative biodegradability of the organic mixture.

Biological oxidation results in the generation of excess sludge and carbon dioxide as the primary end-products. In aerobic systems, such as those employed in the conventional activated sludge process, the respiratory or oxidative reactions provide the energy required for both synthesis and growth of biological population. Also, dissolved oxygen serves as the terminal electron acceptor, and, therefore, is essential for producing the desired end-products. In summary, the biological reactions are controlled by two basic transport mechanisms, as follows:

1. Transport of organics (BOD).
2. Transport of oxygen.

The oxygen transport mechanism is controlled by the transfer rate of oxygen from the gas to the liquid phase, and from the liquid phase to the biological solids. When unlimited oxygen supply is available in the liquid phase, the efficiency of the biological process becomes primarily a function of the capacity of the microorganisms to assimilate organic molecules. The rate of assimilation or the rate of organics removal can be increased by increasing the MLVSS concentration and by intense mixing. Effective mixing of biological solids and organic substrate is accomplished by maintaining high liquid circulation velocities within the Deep Shaft reactor. The liquid flow velocity inside the shaft has been estimated on the order of 1 m/s (3 fps) with a Reynolds number greater than 100,000 (17,18). As a result, high turbulence and intense mixing is achieved within the shaft. The driving force for liquid circulation and mixing is provided by a compressor which serves the dual function of supplying air for both liquid circulation and biological oxidation. The air supply requirements and air injection depth are generally a function of the following:

1. Average and maximum design flow rate.

2. Strength of wastewater undergoing treatment.

3. Shaft diameter and associated friction losses due to fluid dlow.

Since the Deep Shaft biological treatment process utilizes the same process concepts as the activated sludge process, the classical relationships between such process design parameters as the BOD_5 loading ratio (F/M), oxygen requirements per kg BOD_5 removed, waste sludge production (kg TSS per kg BOD_5 removed) are also applicable for the process design of the Deep Shaft biological reactor.

The Deep Shaft process differs from conventional activated sludge systems in terms of equipment design and operating features. These features include the high mixed liquor suspended solids, mode and efficiency of oxygen transfer, flow regime, and type of solids separation process. These design and operating features are summarized in Table 4.

<u>Oxygen Transfer</u>

Proper design of an oxygen transfer system is essential to maintain desired minimum dissolved oxygen concentration values under both average and peak loading conditions. On a conventional activated sludge system using diffused air or mechanical surface aeration, the oxygen transfer rate is limited by the driving force (concentration differential) across the air/water interface to approximately o.2 $kg/m^3 \cdot h$. As a result, the operating paramaters (mixed liquor volatile suspended solids, organic loading ratio, etc.) should be carefully selected such that the oxygen demand values will not exceed the oxygen transfer capabilities. The basic expression involved in estimating the oxygen transfer rate is:

$$dc/dt = K_{LA}(C_{SW} - C) \qquad (2)$$

TABLE 4. COMPARATIVE DESIGN AND OPERATING CRITERIA OF SELECTED ACTIVATED SLUDGE PROCESSES FOR TREATING DOMESTIC WASTEWATER(9)

Parameter	Deep Shaft Flotation Mode Without Primary Clarification	Air Activated Sludge		Oxygen Activated Sludge	
		Without Primary Clarification	With Primary Clarification	Without Primary Clarification	With Primary Clarification
Bioreactor					
Nominal detention time, hr	0.5-0.75	6-8	5-7	1.5-2.5	1.25-1.75
MLSS, mg/L	7,000-12,000	2,000-3,000	1,500-2,500	4,000-6,000	3,500-5,000
% Volatile	0.6-0.7	0.65-0.75	0.7-0.8	0.65-0.75	0.7-0.8
F/M loading, kg BOD_5/kg MLVSS·d	0.75-1.25	0.3-0.5	0.25-0.45	0.55-0.8	0.5-0.75
Volumetric organic loading:					
kg $BOD_5/m^3 \cdot d$	5.6-8.0	0.5-0.8	0.4-0.65	2.2-3.2	2.0-2.8
lb BOD_5/day/1,000 cu ft	350-500	30-50	25-40	135-200	125-175
Sludge retention time,[1] days	2-4	3-6	4-8	1-2	2-3
Solids Separation Unit					
Surface overflow rate:					
Average, $m^3/m^2 \cdot d$	20-29	20-29	20-29	18-26	20-29
gpd/sq ft	500-700	500-700	500-700	450-650	500-700
Peak, $m^3/m^2 \cdot d$	41-49	41-49	41-49	37-45	41-49
gpd/cu ft	1,000-1,200	1,000-1,200	1,000-1,200	900-1,100	1,000-1,200

TABLE 4. (CONTINUED)

Parameter	Deep Shaft Flotation Mode Without Primary Clarification	Air Activated Sludge		Oxygen Activated Sludge	
		Without Primary Clarification	With Primary Clarification	Without Primary Clarification	With Primary Clarification
Mass loading, kg $TSS/m^2 \cdot d$	293-439	73-122	49-98	146-195	122-171
lb TSS/day/sq ft	60-90	15-25	10-20	30-40	25-35
Return sludge flow rate, % of Q	15-25, float 30-50, bottom	25-45	25-50	30-60	30-70
Return sludge concentration, % TSS	7-10, float 3-4, bottom	0.8-1.2	0.6-1.0	1.2-2.0	1.0-1.5
Air, Oxygen, and Power Requirements					
Air supply rate, m^3/kg BOD_5 removed	6-25[3]	50-94[4]		-	
cu ft/lb BOD_5 removed	100-400[3]	800-1,500[4]		-	
Oxygen utilized, kg/kg BOD_5 removed	2.0-2.4	0.9-1.3		1.0-1.4	
Oxygen transfer efficiency in wastewater, % (O_2 utilized/O_2 supplied)	40-90[3]	8-15[4]		90-95	
Oxygen transfer rate in wastewater:					
kg O_2/wire kWh	0.9-2.7[3]	0.9-1.5[4]		1.2-1.5[5]	
lb O_2/wire hp-hr	1.5-4.5[3]	1.5-2.5[4]		2.0-2.5[5]	
Aeration system power requirement:					
Wire kWh/1,000 m^3	80-289	112-177	64-112	121-145	72-88
Wire hp-hr/mil gal	500-1,800	700-1,100	400-700	750-900	450-550

TABLE 4. (CONTINUED)

Parameter	Deep Shaft Flotation Mode Without Primary Clarification	Air Activated Sludge		Oxygen Activated Sludge	
		Without Primary Clarification	With Primary Clarification	Without Primary Clarification	With Primary Clarification
Sludge Production					
Primary sludge TSS,[6] g/m^3	-	-	132	-	132
lb/mil gal	-	-	1,100	-	1,100
Waste activated sludge:					
VSS, g/m^3	72-90	96-132	54-78	96-120	54-66
lb/mil gal	600-750	800-1,100	450-650	800-1,000	450-550
kg/kg BOD_5 removed	0.4-0.5	0.55-0.75	0.5-0.7	0.55-0.65	0.5-0.6
TSS, g/m^3	108-138	138-186	72-102	138-168	72-90
lb/mil gal	900-1,150	1,150-1,550	600-850	1,150-1,400	600-750
kg/kg BOD_5 removed	0.6-0.75	0.75-1.05	0.65-0.95	0.75-0.95	0.65-0.8
Total plant raw and waste sludge TSS:					
g/m^3	108-138	138-186	204-234	138-168	204-222
lb/mil gal	900-1,150	1,150-1,550	1,700-1,950	1,150-1,400	1,700-1,850
Final effluent solids:[7]					
VSS, g/m^3	13	14	16	14	16
lb/mil gal	110	120	130	120	130
TSS, g/m^3	20	20	20	20	20
lb/mil gal	170	170	170	170	170

TABLE 4. (CONTINUED)

Parameter	Deep Shaft Flotation Mode Without Primary Clarification	Air Activated Sludge Without Primary Clarification	Air Activated Sludge With Primary Clarification	Oxygen Activated Sludge Without Primary Clarification	Oxygen Activated Sludge With Primary Clarification
Total sludge production (waste and effluent) in secondary system:					
VSS, g/m^3	85-103	110-146	70-94	110-134	70-82
lb/mil gal	710-860	920-1,220	580-780	920-1,120	560-680
kg/kg BOD_5 removed	0.45-0.55	0.6-0.8	0.65-0.85	0.6-0.75	0.65-0.75
TSS, g/m^3	128-158	158-206	92-122	158-188	92-110
lb/mil gal	1,070-1,320	1,320-1,720	770-1,020	1,320-1,570	770-920
kg/kg BOD_5 removed	0.7-0.9	0.9-1.15	0.85-1.1	0.9-1.05	0.85-1.0

[1]Defined as kg MLSS in bioreactor/(kg TSS lost in waste activated sludge and final effluent/day).
[2]Dry weather peak.
[3]Depends on shaft diameter and degree of air tuning in shaft (Eco-II vs. Eco-III).
[4]Lower values representative of coarse bubble diffusers; higher values representative of fine bubble diffusers.
[5]Lower values apply to systems employing pressure swing adsorption (PSA) oxygen generation; higher values apply to systems employing cryogenic oxygen generation.
[6]Calculated on the basis of 65 percent removal of an assumed raw wastewater concentration of 200 mg/L.
[7]Assumes a final effluent TSS of 20 mg/L and final effluent solids volatility in accordance with assumed mixed liquor volatility of respective processes.

The basic expression involved in estimating the oxygen transfer rate is:

$$dc/dt = K_{LA}(C_{SW}-C)$$

where:

dc/dt = the rate of change in dissolved oxygen concentration ($kg/m^3 \cdot h$)

K_{LA} = the oxygen transfer rate coefficient (h^{-1})

C_{SW} = the oxygen saturation concentration in waste-wastewater (mg/L)

C = the minimum dissolved oxygen concentration (mg/L)

According to this expression, the oxygen transfer rate in a specific waste stream or in a mixed liquor can be increased only by increasing the attainable saturation value (C_{SW}).

According to Henry's law, the saturation value can be increased by raising the partial pressure of the gas requiring dissolution. This can be accomplished by either of the following methods:

1. Increasing the mole concentration of oxygen in the source (enriched oxygen systems) such as those used in the pure oxygen activated sludge process.

2. Increasing the system operating pressure as in the case of the Deep Shaft biological reactor.

In a pure oxygen activated sludge system, the oxygen transfer rates are approximately five times greater than in systems using air diffusion or mechanical surface aeration. In the case of a Deep Shaft biological reactor, the operating pressures are increased to 1,520 kPa (15 atm), and, therefore, the oxygen transfer rate is similarly increased to 2,000-3,000 mg/L/h (150 to 200 lb/1,000 cu ft/hr). This increased oxygenation capacity allows the system to operate with higher mixed liquor suspended solids concentrations, and, therefore, with lower aeration periods than in the conventional activated sludge process. A relationship was developed between organic loading ratio (F/M) and the oxygen transfer requirement for various MLVSS's. This relationship is illustrated graphically in Figure 16. An analysis of this figure indicates that there is a limiting loading ratio (F/M) for each mixed liquor suspended solids concentration, above which the oxygen demand requirements cannot be satisfied by conventional methods. For illustrative purposes, the upper limit

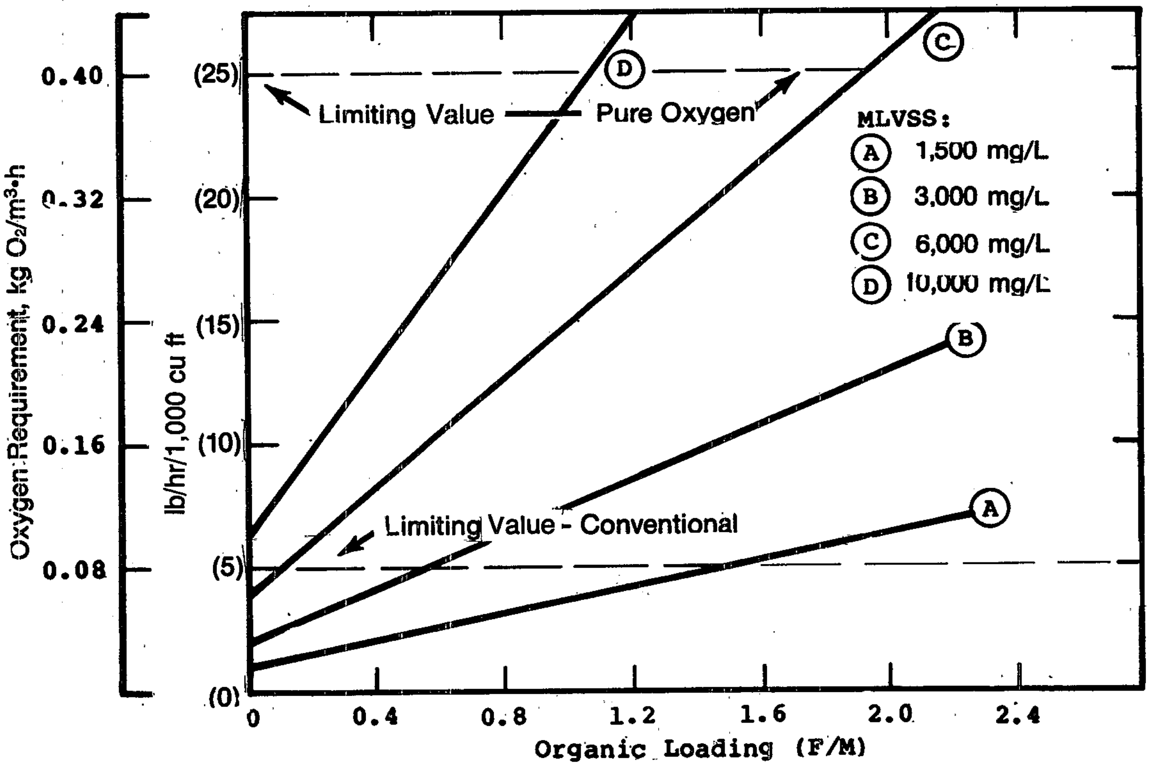


Figure 16. Relationship between organic loading (F/M) and oxygen requirement.

for oxygenation capacity has been assumed at 0.08 kg/m^3·h (5 lb/hr/1,000 cu ft) of aeration volume for conventional air systems. For example, the organic loading ratio (F/M) must be maintained below 0.55 when the operating MLVSS is 3,000 mg/L in order that the aeration capabilities of the conventional equipment will not be exceeded. By reiteration of this technique, a limiting envelope was developed which relates the organic loading ratio (F/M), MLVSS, and oxygenation capacity. Similarly, another limiting envelope was developed for pure oxygen systems with a maximum oxygenation capacity assumed at 0.40 kg/m^3·h (25 lb/hr/1,000 cu ft). Figure 17 shows these limiting envelopes for the conventional and enriched oxygen systems. It is to be recognized that these limiting curves are developed with assumed or preselected values for oxygenation capacities and therefore is for illustrative purposes only. Actual limiting values may differ depending on the aeration device selected for a particular application (e.g., fine bubble, coarse bubble, aeration basin depth, mechanical surface aeration, etc.). In addition, the limiting envelopes for the different technologies may overlap.

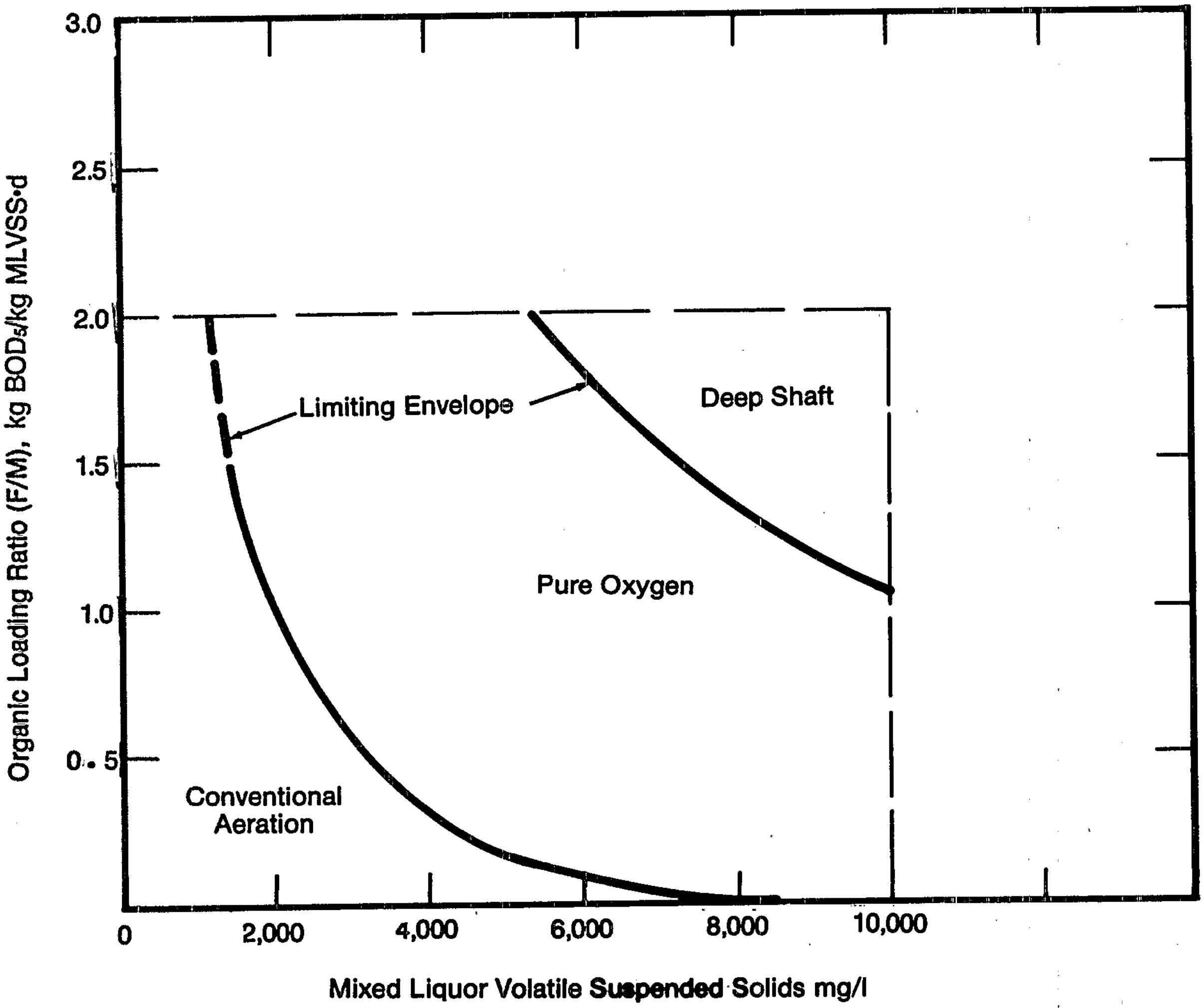


Figure 17. Illustration of oxygen transfer limiting envelopes for conventional and pure oxygen processes based on a maximum capacity of 0.08 $kg/m^3 \cdot h$ (5 lb/hr/1,000 cu ft) for conventional air activated sludge and a maximum oxygenation capacity of 0.40 $kg/m^3 \cdot h$ (25 lb/hr/1,000 cu ft)

It is evident from this process evaluation that one of the major constraints imposed on the design of an aerobic biological treatment process is the capability of the aeration equipment to maintain an aerobic environment. The Deep Shaft process is capable of exceeding these limits as the system can achieve up to 90 percent oxygen transfer efficiency. As a result, organic loading ratios (F/M) as high as 2.0 can be used with mixed liquor volatile suspended solids concentration values of up to 10,000 mg/L, thereby reducing the aeration periods to 30 minutes or less.

<u>Solids Separation</u>

One of the major considerations in the design of an aerobic biological wastewater treatment system involves the incorporation of an effective solids separation process unit. Gravity sedimentation units have served this purpose reasonably well within the operating range for conventional systems (MLSS between 2,000 and 3,000 mg/L) and oxygen-enriched systems (MLSS between 4,000 and 6,000 mg/L). These units serve the dual purpose of producing a clarified effluent and a source of sludge for recirculation. This latter function is critical in maintaining the biological integrity of the aeration basin to produce a flocculant biomass which can readily settle. Extensive studies on the gravity settling and thickening characteristics of activated sludge have indicated that the process is effective when the suspended solids concentration values are maintained below 6,000 mg/L.[10,11] This will permit operating the gravity sedimentation units with a reasonable sludge blanket depth (0.25 to 1 m) and within a recommended solids flux of 29 to 120 $kg/m^2 \cdot day$ (6 to 25 lb/day/sq ft).

Earlier versions of the Deep Shaft process recognized these limitations and the process was designed to operate with suspended solids concentration values between 5,000 and 6,000 mg/L. However, the North American versions of the Deep Shaft process (Eco-I, Eco-II, and Eco-III) have adopted a dissolved air flotation process as the terminal unit operation, and utilize the available dissolved gases. The dissolved gases present in the Deep Shaft reactor simulate the pressure vessel in the dissolved air flotation process, and provide the driving force during solids separation. The process possesses additional advantages in producing a significantly higher float solids concentration (4 to 7%) than the underflow solids concentration from a typical gravity sedimentation unit (1 to 3%). Table 5 summarizes the design and operating features of the two concepts.[19]

TABLE 5. DESIGN AND OPERATING PARAMETERS FOR A DEEP SHAFT SOLIDS SEPARATION PROCESS[19]

Parameter	Flotation Mode	Sedimentation Mode
Hydraulic overflow rate, $m^3/m^2 \cdot d$ (gpd/sq ft)	20 (500)	10 (250)
Mass loading, $kg/m^2 \cdot d$ (lb/day/sq ft)	320 (66)	103 (21)
Float solids concentration %	7-10	ND[1]
Sink solids concentration %	3-4	1-2

[1]ND: No Data.

Biological Concepts

Principally, the Deep Shaft biological treatment process involves the use of aerobic metabolic capabilities for converting dissolved organics into gaseous (CO_2) and solid (waste sludge) end products. The Deep Shaft process differs from the conventional activated sludge process with respect to its flow regime, operating pressure, and oxygen tension inside the reactor. A study initiated to compare the effects of these process features on the biological properties of the sludge revealed that the waste sludge from the Deep Shaft process does not differ significantly from those experienced in conventional activated sludge systems.[16] The results of this study are summarized in Table 6.

Design Considerations

The Deep Shaft biological reactor differs from the conventional activated sludge process as oxygen transfer is not accomplished at atmospheric pressure.

TABLE 6. COMPARISON BETWEEN DEEP SHAFT AND CONVENTIONAL ACTIVATED SLUDGE (6)

Sludge Properties[1] (or) Components	Deep Shaft Reactor	Conventional Activated Sludge
ATP content (mg/L)	0.806	0.537-0.991
Specific oxygen uptake rate (g/kg.h)	40	14.5-57.7
Michaelis-Menton[2] growth constant - K_s (mg/L)	50	20-50
Physical Characteristics[3]		
Specific resistance, m/kg x 10^{14}	1.29	8.54[3]
Compressibility index	0.85	0.78
Waste sludge concentration, %	2.1	0.94

[1]Average values for sludge properties are reported; comparison was made of sludges produced from the treatment of primarily domestic wastewaters.

[2]Refers to the concentration of BOD_5 (raw wastewater) at which the specific oxygen uptake rate is one-half the maximum value. The term "Michaelis-Menton Growth Constant" is used for comparison of specific oxygen uptake rate values because of the belief that the theory of enzyme reaction kinetics is directly applicable in describing the growth or BOD_5 removal kinetics in the activated sludge process.

[3]Physical characteristics for waste activated sludge from conventional air activated sludge was determined utilizing aerobically-digested sludge samples.

The activated sludge process requires relatively large amounts of energy to transfer adequate amounts of oxygen for carrying out the biological reactions. When these demands exceed the oxygen transfer capabilities of conventional equipment (diffused air or mechanical surface aeration), the aeration basin volume is generally increased to balance the oxygen demand-supply characteristics. As a result, the design and operating characteristics of conventional systems are often dictated by the limitations imposed by oxygen transfer equipment. Deep Shaft biological reactors are designed to operate with 90 to 250 m (300 to 800 ft) of hydrostatic pressure with oxygenation capacities between 2,000 and 3,000 mg/L•h. As a result, the design of Deep Shaft biological reactors is basically dependent on the organic removal rate and the availability of a consistent source of recycle biomass. In general, the design of a biological reactor involves consideration of the following:

1. Providing adequate mixing to maintain mixed liquor solids in suspension, and to improve the opportunity for contact between biological solids and organics.

2. Providing adequate residence time in the reactor for achieving the desired removal efficiency.

3. Providing adequate facilities for recycling sludge and for maintaining the desired mixed liquor volatile suspended solids concentration.

Mixing in Deep Shaft reactors is accomplished by maintaining sufficient velocities and turbulence through the shaft (1 to 2 m/s). During startup, the flow inside the Deep Shaft is initiated by injecting air into the riser section. The differential hydrostatic head, developed due to the voidage difference between the downcomer and the riser sections, is adequate to initiate and maintain flow through the shaft. The driving force (y) required to maintain flow through the reactor is estimated from the voidage head difference and the friction loss, as follows:

$$y = (\text{voidage head} - \text{friction loss}) \quad (3)$$

In general, the voidage head difference is adjusted by controlling the air injection depth to the downcomer. The air requirements and the air injection depth are usually selected to maintain forward flow under all conditions (average and peak flow conditions). For domestic wastewaters ($BOD_5 \simeq 200$ mg/L), the air flow requirements are primarily dictated by the required driving force to maintain flow. In the case of high strength wastewaters, the air flow requirements may be dictated by the wastewater's organic strength and oxygen requirements.

The residence time and extremely high pressure (up to 1,520 kPa; 15 atm) available in the lower sections of the Deep Shaft reactor are sufficient to achieve nearly complete dissolution of oxygen. For design purposes, it is usually assumed that 90 percent of the oxygen supply goes into solution during passage through the reactor. This is equivalent to 0.25-kg oxygen for each cubic meter of air injected into the reactor. The total air requirements for biological oxidation can thus be estimated from the raw wastewater characteristics and treatment requirements.

Optimization studies conducted with air diffusion in Deep Shaft reactors indicate that, at 90-percent oxygen absorption efficiency, oxygen demand rates of up to 1 $kg/m^3.h$ can be satisfied with a 135 m (450 ft) deep reactor. In general, an operating depth of between 100 and 150 m (328 to 492 ft) is usually selected for design of the Deep Shaft reactors, taking into consideration the patent regulations on other similar processes (e.g., U-tube aeration).[20] Figure 18 shows the dissolved oxygen and BOD profiles normally anticipated inside Eco-II or Eco-III reactor systems.

PROCESS CAPABILITIES AND LIMITATIONS

Process Capabilities

Deep Shaft biological reactors have the same process concepts and capabilities as conventional activated sludge systems. Because of the high mixed liquor volatile solids maintained in the Deep Shaft reactor, volumetric organic removal rates are higher than in the equivalent conventional concept. As a result, the aeration period is relatively low and is on the order of 30 to 60 minutes. Based on an average flow-through velocity of 1 m/s (3.05 ft/sec) inside the Deep Shaft reactor, the average turnover rate for the mixed liquor is approximately once every 5 minutes when the reactor depth is 150 m (457 ft).[21] This circulating turbulent mixed liquor serves as the dilution medium for the influent waste stream to the reactor. The dilution factor is a function of the mean residence time (t) of the influent waste stream in the reactor and the flow-through velocity inside (v). The dilution factor can be expressed as follows:

$$\frac{Q_i}{Q_R} = \frac{(H/v)}{t} \qquad (4)$$

where:

Q_i = Influent waste flow rate in m^3/h

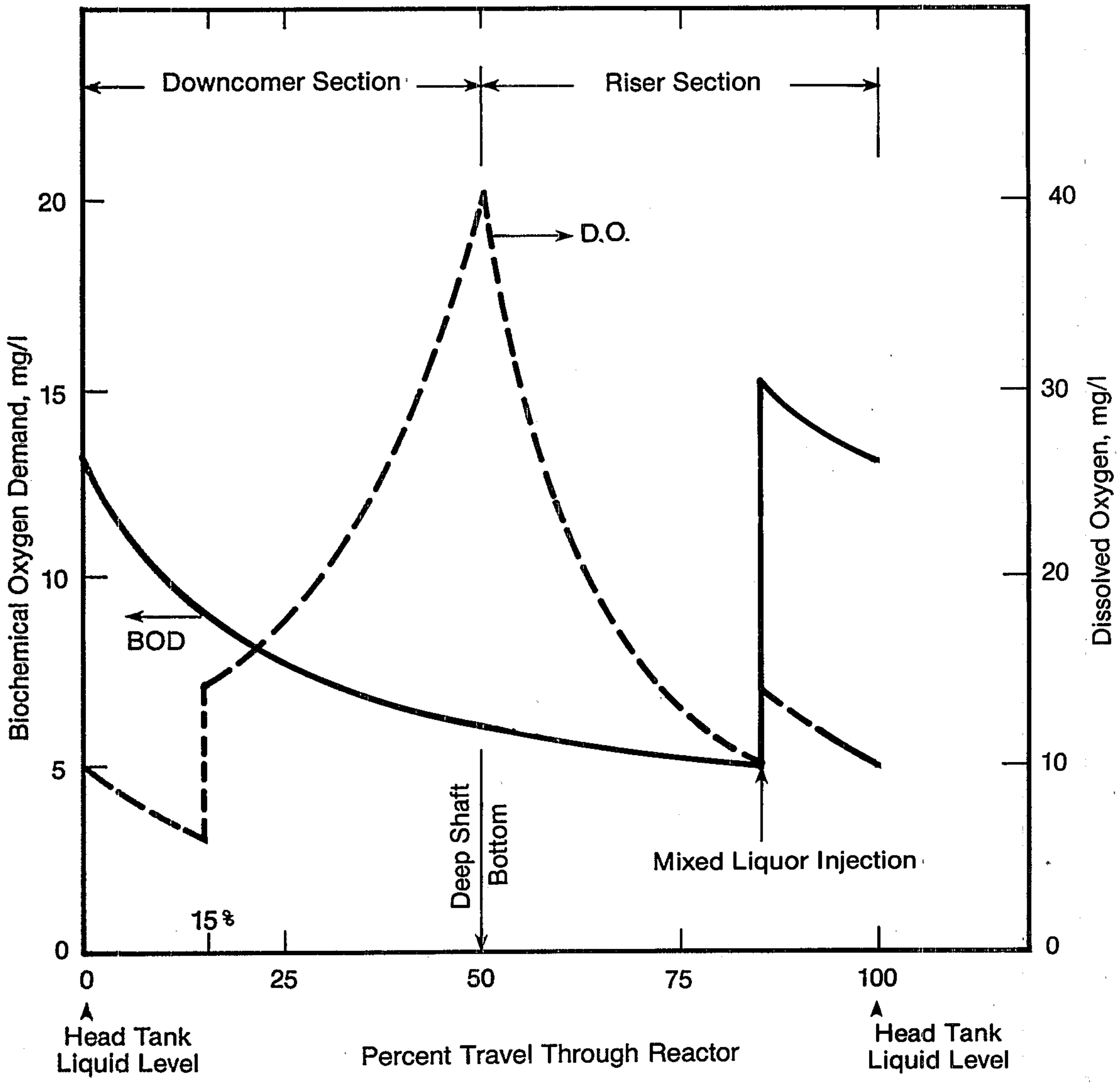


Figure 18. Dissolved oxygen and BOD profile for Eco-II and Eco-III Deep Shaft reactors.

Q_R = Mixed liquor flow rate through the Deep Shaft in m^3/h

H = Depth of Deep Shaft in m

v = Flow-through velocity inside the reactor, m/h

t = Mean residence in the reactor, h

This design feature of the Deep Shaft reactor aids in minimizing the effects of shock loads on system performance.

Even though the flow pattern inside the reactor resembles plug flow for each passage, the mixed liquor turnover rate and the external dilution aid the system to approach complete-mix status, and therefore the system is relatively stable to variations in influent characteristics. Figure 19 shows the comparison in concentration profile within completely mixed, plug flow, and Deep Shaft reactors.

Because of the ability of the Deep Shaft reactor to achieve oxygen transfer efficiencies of up to 90 percent, the system is suitable for the joint treatment of high-strength industrial and municipal wastewaters. Similarly, the system is also suitable for pretreatment of industrial wastewaters.(22, 23,24)

Process Limitations

Because of the relatively low residence time utilized in the design of the Deep Shaft reactors, the system is susceptible to upsets due to sustained hydraulic peak flows. The Eco-III reactor design recognizes this problem and is equipped with a two-speed drive mechanism for the float skimmer for adjusting the recycle sludge flow rate. For the same reason, it is essential to adequately define the average and maximum flow conditions during the design of a Deep Shaft reactor.

The Deep Shaft process is more difficult and expensive to expand than conventional activated sludge processes because of the cost and time involved in drilling and mobilization of drilling equipment. Most often, it may be necessary to expand by doubling the capacity of the existing plant because of the shaft placement economics.

Even though the process has been tested for use in aerobic digestion studies, the results of these studies have not been reported or published for evaluation during this investigation. Preliminary discussions with Eco-Technology personnel indicate that successful digestion has been achieved with a digestion

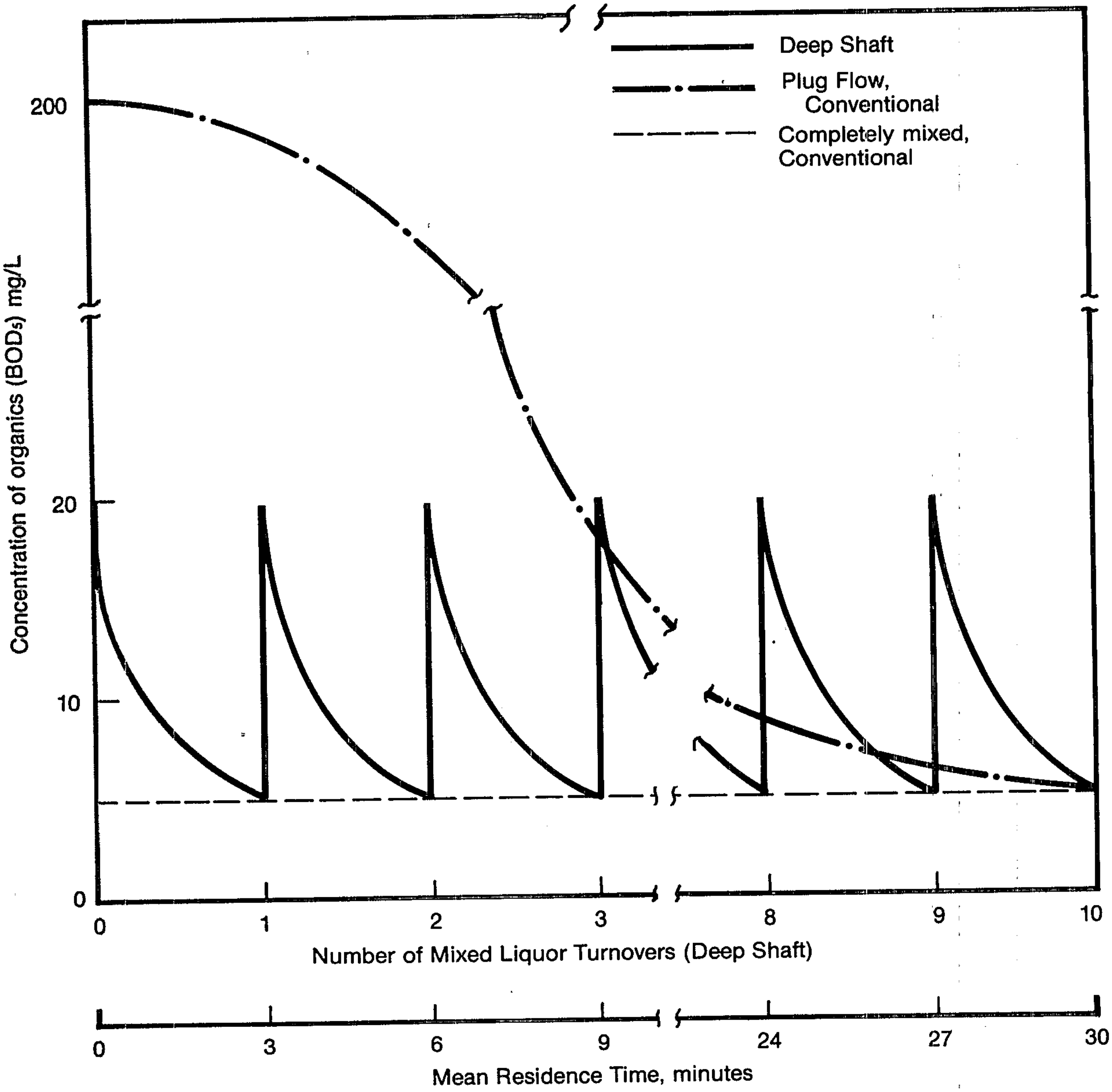


Figure 19. Comparison of concentration profiles for conventional and Deep Shaft reactor systems.

period of 3 to 4 days. From process considerations, the Deep Shaft system appears suitable for aerobic digestion. However, the higher digestion rate coefficient ($days^{-1}$) achieved in preliminary testing has yet to be demonstrated in a long-term dedicated facility. It is also necessary to demonstrate that the Deep Shaft digester can handle solids concentrations in the range of 7 percent which is the expected float solids concentration.

OPERATION AND MAINTENANCE CONSIDERATIONS

The Deep Shaft reactor, as shown in Figures 10 and 11, is very simple in configuration and has no moving parts inside the shaft. As a result, the requirement for maintenance of the shaft components themselves is minimal and expected to be less than those anticipated for conventional activated sludge processes equipped with air diffusers. The high pressure (790 kPa; 100 psi) compressors used in the Deep Shaft process, however, will require increased maintenance as compared to the low pressure blowers (<79 kPa) or mechanical surface aerators used in conventional systems.[23] Similarly, the operation of the dissolved air flotation process will require additional training and increased operator monitoring as compared to a gravity sedimentation process.

The Eco-III version of the Deep Shaft reactor has eliminated most automatic instrumentation and controls, thereby making it less complicated than conventional processes. This is especially true with respect to the sludge recirculation system which is set at a constant rate during normal flow conditions.

Because the Deep Shaft reactors are installed subsurface, the mixed liquor inside the reactor is not subject to wide seasonal variations in temperature. Therefore, process operating parameters can be maintained at a steady rate year-round and less operator attention will be required. A disadvantage of the Deep Shaft process, however, is the inability to visually observe mixed liquor contents so that process upsets can be detected immediately.

In general, the Deep Shaft process is not appreciably different from conventional activated sludge systems, and it is not expected to require any specialized skills. Therefore, the staffing requirements will be similar to the conventional systems of equivalent size. Because of this similarity, the Deep Shaft process may be suitable for expanding existing activated sludge plants where space restrictions prevail.

COST CONSIDERATIONS

The application of the Deep Shaft wastewater treatment process has been demonstrated successfully for the treatment of domestic and industrial wastewaters. This experience is mostly limited to European and Canadian practice. One 0.46-m (18-in.) diameter demonstration unit has been installed and has been in operation in Ithaca, New York since 1979. This system is designed to handle a mixture of industrial and domestic wastewater and is equipped with facilities to operate either in the sedimentation or the flotation mode.

Based on current experience with the Deep Shaft process, the major cost element is associated with the installation of the reactor itself. The fixed cost associated with well drilling and shaft installation, including electrical, mechanical and instrumentation devices, has been estimated to be between 30 and 50 percent of the total project cost.[25,26,27] The cost of drilling is subject to variation depending on geological conditions, the availability of drilling rigs, and their demand for other more competitive purposes (e.g., oil well drilling, etc.).

ENERGY CONSIDERATIONS

The major energy requirement in biological wastewater treatment systems is the biological reactor in which the oxygen demand requirements must be supplied from external sources. The Deep Shaft process is no exception to this requirement, since the oxygen is supplied using high pressure compressors with discharge pressures of ~790 kPa (100 psi). The actual energy requirements for a Deep Shaft reactor are governed by the following:

1. Organic and hydraulic load for average and peak conditions.

2. Mixed liquor volatile suspended solids (MLVSS).

3. Air requirements for liquid circulation.

4. Shaft diameter.

In general, shafts smaller than 1 m (3 ft) in diameter may require supplemental air to maintain mixed liquor circulating velocities in treating normal strength domestic wastewater.[24] When optimum organic loading conditions prevail, oxygen transfer efficiencies up to 6 kg O_2/kwh (9.8 lb O_2/ hp) can be realized.[7] On the other hand, small diameter shafts treating weak wastewaters can realize power economies in the range between 2 and 3 kg O_2/kwh (3.3 - 4.9 lb O_2/hp).

SECTION 4

COMPARISON WITH EQUIVALENT TECHNOLOGY

EQUIVALENT CONVENTIONAL CONCEPT

The Deep Shaft treatment system is a high rate activated sludge process in which the shallow aeration basins of 3 to 10 m (9 to 30 ft) are replaced with deep subsurface reactors of 90 to 250 m (270 to 760 ft). In addition, the North American version of the Deep Shaft process utilizes dissolved air flotation for final clarification of mixed liquor suspended solids. In an attempt to select the most suitable equivalent technology, the conventional activated sludge process and its modifications were evaluated during initial screening. Upon closer examination of the various operating parameters, however, the decision was made to use the enriched oxygen process (pure oxygen) for the purposes of comparing equivalent technology. Aside from other similarities, the pure oxygen system is usually designed to operate with high mixed liquor suspended solids (4,000 to 6,000 mg/L) and with a high dissolved oxygen concentration (5 to 7 mg/L). These design features allow the biosystem to operate under high organic loadings (F/M) and with reduced aeration volume similar to those achievable in the Deep Shaft process.

Other similarities between the pure oxygen activated sludge and the Deep Shaft alternatives include the high oxygen tension within the bio-reactor and the claimed resultant low waste sludge generation. A comparative analysis of these design features and operating criteria are presented in Table 4 in the technology evaluation section of this report (Section 3). This comparison indicates that design criteria such as the nominal detention time, mixed liquor suspended solids (MLSS), organic loading, and sludge age are within the same range for the oxygen-activated sludge and the Deep Shaft process. In general, the comparative analysis of design and operating criteria indicates that the two processes are similar except for the oxygen utilization efficiency and the return sludge concentration values. For these reasons, the pure oxygen system was selected as the equivalent technology for comparison with the Deep Shaft process. The air-activated sludge process was included in the evaluation in order to establish a baseline technology in the comparative analysis. For the 1,892 m^3/d (0.5 mgd) facility, conventional activated sludge was used as the baseline technology, wheras high-rate activated sludge was used as the baseline technology for the 18,925 m^3/d (5.0 mgd) and 37,850 m^3/d (10.0 mgd) facilities.

Cost Comparison

The economic analysis of the three different technologies considered the initial investment cost (capital cost), the annual operation and maintenance cost, and the present worth cost of the total treatment system. Cost estimates developed by the U.S. EPA for evaluating innovative and alternative technologies(1) were used as the primary source for estimating installed capital and annual operation and maintenance costs for the pure oxygen and conventional activated sludge processes. These cost estimates were supplemented with cost figures from Appendix H of the Areawide Assessment Procedures manual to include structural and nonstructural cost components (e.g., influent pumping or lift station, and miscellaneous structures such as control and operations buildings, outfall sewer, etc.).(33)

For the Deep Shaft alternative, the turn-key cost estimates for the Deep Shaft portion of the facilities were obtained from Eco Technology. The battery limits for the Deep Shaft portion included the Deep Shaft reactor(s), flotation separator units, and the control building for these components. These cost estimates were supplemented with estimates for remaining process units (e.g., sludge handling and treatment, preliminary treatment, disinfection, influent and effluent structures, etc.) utilizing the same cost curves as the equivalent and baseline technology alternatives. All cost estimates were updated to reflect December 1980 construction costs (Engineering News Record Index 3376). The basic assumptions and procedures utilized in estimating construction costs are summarized in Appendix A.

Taking into consideration the current status of development and experience with the Deep Shaft system, three design flows were selected for comparison. The three design flows are:

1. 1,892 m^3/d (0.5 mgd)
2. 18,925 m^3/d (5.0 mgd)
3. 37,850 m^3/d (10.0 mgd)

For the Deep Shaft system, Eco Technology provided turnkey cost estimates for 1,892, 18,925, and 189,250 m^3/d (0.5-, 5.0-, and 50-mgd) capacities. These cost estimates, together with updated bid estimates for three full-scale Canadian plants (Virden, Molson Breweries, and Portage La Prairie), were used as the basis for estimating Deep Shaft system costs for the 37,850 m^3/d (10.0 mgd) plant size. The design data and fact sheets for these facilities are included in Appendix B. Tables 7, 8, and 9 show the results of cost evaluations for the three systems. All capital cost estimates reflect December 1980 cost figures (Engineering New Record Index 3376).

Energy Requirements

An approach similar to that utilized for the cost comparison was used for estimating the energy requirements for the three different technologies. All information relative to operations within the battery limits of the Deep Shaft system was obtained from the Eco Technology personnel. The energy requirements for operations outside the battery limits of vendor-supplied components were estimated utilizing the EPA-developed information for evaluating innovative and alternative technologies. The analyses of energy requirement are summarized in Tables 10, 11, and 12.

Land Area Requirements

One of the significant advantages of the Deep Shaft system is the reduced land area requirement as compared to the conventional air or pure oxygen activated sludge systems. This feature makes the Deep Shaft system especially attractive for consideration in land restricted areas, and in expanding existing facilities where land availability is limited. Figure 20 shows the relative land area requirements for the Deep Shaft and conventional air-activated sludge systems. Based on the design criteria presented in Table 4, it is likely that the land area requirements for the pure oxygen-activated sludge system will be similar to the conventional air-activated sludge process. This is due to the fact that any space reductions realized in aeration tank sizing will be compensated by the additional area required for installing oxygen supply equipment.

TABLE 7. COST COMPARISON -- 1,892 m^3/d (0.5 mgd) FACILITY[1]

Process Unit	Conventional Activated Sludge (Baseline)	Pure Oxygen (Equivalent)	Deep Shaft
Low-lift pumping	$ 171,000	$ 171,000	$ 171,000
Preliminary treatment	40,900	40,900	40,900
Aeration/clarification	464,000	896,000	900,000[2]
Disinfection (chlorination)	54,600	54,600	54,600
Gravity outfall	218,000	218,000	218,000
Aerobic digestion	239,000	164,000	81,800
Vacuum filtration	273,000	273,000	273,000
Sludge hauling and landfilling	131,000	131,000	131,000
Miscellaneous structures	68,200	68,200	68,200
Subtotal	$1,659,700	$2,016,700	$1,038,500[4]
Noncomponent costs[3]	465,000	565,000	291,000[4]
Engineering, construction supervision	319,000	387,000	199,000[4]
Contingency	319,000	387,000	199,000[4]
Total installed capital cost	$2,762,700	$3,355,700	$2,627,500
Annual operation and maintenance costs	$ 175,000	$ 184,500	$ 200,000
Present worth cost[5]	$4,563,800	$5,254,600	$4,685,000

[1]See Appendix A for details of assumptions used in the cost analysis.
[2]Turnkey cost, including noncomponent costs, engineering, construction supervision, and contingency.
[3]Noncomponent costs include piping, electrical, instrumentation, and site preparation.
[4]Exclusive of Deep Shaft costs which are turnkey costs.
[5]Present worth computed assuming 20-year life at 7-3/8% interest rate (PWF = 10.29213).

TABLE 8. COST COMPARISON -- 18,925 m^3/d (5.0 mgd) FACILITY[1]

Process Unit	High-Rate Activated Sludge (Baseline)	Pure Oxygen (Equivalent)	Deep Shaft
Low-lift pumping	$ 614,000	$ 614,000	$ 614,000
Preliminary treatment	171,000	171,000	171,000
Primary clarifier	382,000	382,000	-
Aeration/clarification	1,132,000	2,956,000	3,300,000[2]
Disinfection (chlorination)	140,000	140,000	140,000
Gravity outfall	709,000	709,000	709,000
DAF thickening	171,000	171,000	-
Anaerobic digestion	546,000	546,000	423,000
Vacuum filtration	464,000	464,000	464,000
Sludge hauling and landfilling	185,000	185,000	185,000
Miscellaneous structures	232,000	232,000	232,000
Subtotal	$4,746,000	$6,570,000	$2,938,000[4]
Noncomponent costs[3]	1,330,000	1,840,000	823,000[4]
Engineering, construction supervision	911,000	1,260,000	564,000[4]
Contingency	911,000	1,260,000	564,000[4]
Total installed capital cost	$7,898,000	$10,930,000	$8,189,000
Annual operation and maintenance costs	$ 459,200	$ 498,900	$ 513,400
Present worth cost[5]	$12,624,000	$16,065,000	$13,473,000

[1]See Appendix A for details of assumptions used in cost analysis.
[2]Turnkey cost, including noncomponent costs, engineering, construction supervision, and contingency.
[3]Noncomponent costs include piping, electrical, instrumentation, and site preparation.
[4]Exclusive of Deep Shaft costs which are turnkey costs.
[5]Present worth computed assuming 20-year life at 7-3/8% interest rate (PWF = 10.29213).

TABLE 9. COST COMPARISON -- 37,850 m^3/d (10 mgd) FACILITY[1]

Process Unit	High-Rate Activated Sludge (Baseline)	Pure Oxygen (Equivalent)	Deep Shaft
Low-lift pumping	$ 955,000	$ 955,000	$ 955,000
Preliminary treatment	259,000	259,000	259,000
Primary clarifier	573,000	573,000	-
Aeration/clarification	1,773,000	4,265,000	5,600,000[2]
Disinfection (chlorination)	273,000	273,000	273,000
Gravity outfall	1,090,000	1,090,000	1,090,000
DAF thickening	205,000	205,000	-
Anaerobic digestion	791,000	791,000	436,000
Vacuum filtration	614,000	614,000	614,000
Sludge hauling and landfilling	235,000	235,000	235,000
Miscellaneous structures	327,000	327,000	327,000
Subtotal	$7,095,000	$9,587,000	$4,189,000[4]
Noncomponent costs[3]	1,990,000	2,684,000	1,170,000[4]
Engineering, construction supervision	1,360,000	1,840,000	804,000[4]
Contingency	1,360,000	1,840,000	804,000[4]
Total installed capital cost	$11,805,000	$15,951,000	$12,567,000
Annual operation and maintenance costs	$ 714,800	$ 768,000	$ 699,200
Present worth cost[5]	$19,162,000	$23,855,000	$19,763,000

[1]See Appendix A for details of assumptions used in cost analysis.

[2]Turnkey cost, including noncomponent costs, engineering, construction supervision, and contingency.

[3]Noncomponent costs include piping, electrical, instrumentation, and site preparation.

[4]Exclusive of Deep Shaft costs which are turnkey costs.

TABLE 10. ENERGY ANALYSIS (kWh/y)--
1,892 m^3/d (0.5 mgd) FACILITY[1]

Process Unit	Conventional Activated Sludge (Baseline)	Pure Oxygen (Equivalent)	Deep Shaft
Low-lift pumping	9,000	9,000	9,000
Preliminary treatment	14,000	14,000	14,000
Aeration/clarification	195,000	45,000[2]	268,000
Disinfection (chlorination)	5,000	5,000	5,000
Gravity outfall	-	-	-
Aerobic digestion	90,000	90,000	90,000
Vacuum filtration	62,500	62,500	62,500
Sludge hauling and landfilling	53,100	53,100	53,100
Total kWh/y	428,600	278,600	501,600
Energy utilization, kWh/km^3	621	403	726
kg BOD_5 removed/kWh	0.274	0.422	0.234

[1]See Appendix A for details of assumptions used in cost analysis.
[2]Assumes purchase of liquid oxygen.

TABLE 11. ENERGY ANALYSIS (kWh/y)--
18,925 m^3/d (5.0 mgd) FACILITY[1]

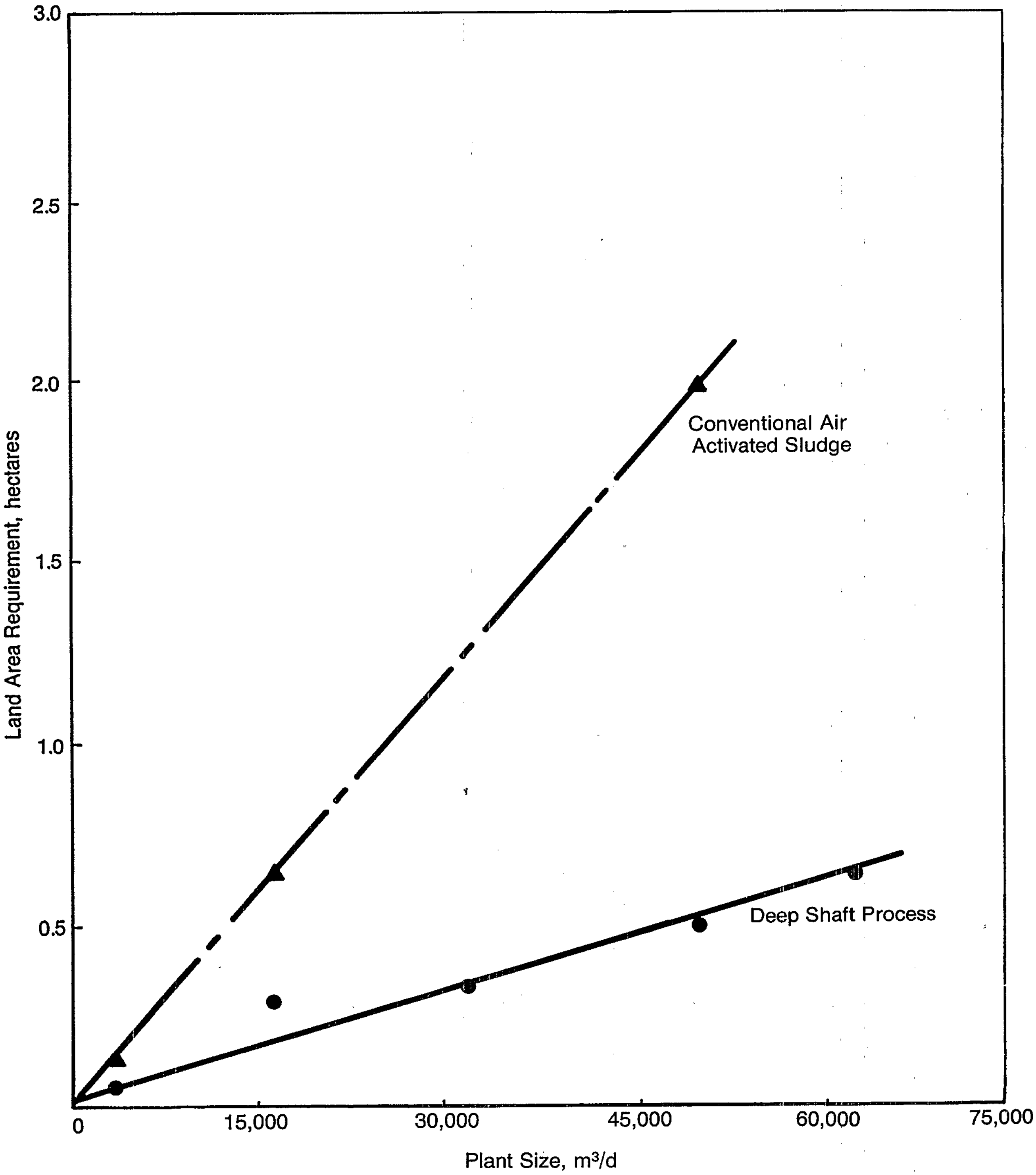
Process Unit	High-Rate Activated Sludge (Baseline)	Pure Oxygen (Equivalent)	Deep Shaft
Low-lift pumping	90,000	90,000	90,000
Preliminary treatment	17,500	17,500	17,500
Primary clarifier	45,000	45,000	-
Aeration/clarification	565,000	765,000	2,450,000
Disinfection (chlorination)	11,000	11,000	11,000
Gravity outfall	-	-	-
DAF thickening	130,000	130,000	-
Anaerobic digestion	20,000	20,000	13,500
Vacuum filtration	62,500	62,500	62,500
Sludge hauling and landfilling	350,000	350,000	350,000
Total kWh/y	1,291,000	1,491,000	2,994,500
Energy utilization, kWh/km^3	187	216	434
kg BOD_5 removed/kWh	0.911	0.789	0.393

[1]See Appendix A for details of assumptions used in cost analysis.

TABLE 12. ENERGY ANALYSIS (kWh/y)--
37,850 m^3/d (10 mgd) FACILITY[1]

Process Unit	High-Rate Activated Sludge (Baseline)	Pure Oxygen (Equivalent)	Deep Shaft
Low-lift pumping	180,000	180,000	180,000
Preliminary treatment	21,800	21,800	21,800
Primary clarifier	77,000	77,000	-
Aeration/clarification	1,400,000	1,400,000	3,400,000
Disinfection (chlorination)	12,500	12,500	12,500
Gravity outfall	-	-	-
DAF thickening	250,000	250,000	-
Anaerobic digestion	40,000	40,000	24,000
Vacuum filtration	110,000	110,000	110,000
Sludge hauling and landfilling	701,000	701,000	701,000
Total kWh/y	2,792,300	2,792,300	4,449,300
Energy utilization, kWh/km^3	202	202	322
kg BOD_5 removed/kWh	0.842	0.842	0.529

[1]See Appendix A for details of assumptions used in cost analysis.



Source of Data: Reference No. 5

Figure 20. Land area requirements for conventional air-activated sludge and Deep Shaft aeration process.

SECTION 5

NATIONAL IMPACT ASSESSMENT

MARKET POTENTIAL

A review of the "1978 Needs Survey for Conveyance and Treatment of Municipal Wastewaters" indicates that the current secondary treatment technology can be classified into three major categories, as follows:

1. Trickling filter and its modifications.

2. Activated sludge and its modifications.

3. Other processes, including rotating biological contactors, oxidation ditches, etc.

The Needs Survey data on a number of wastewater treatment plants indicate that there is an increasing trend toward the use of the activated sludge process, or its modifications, for plants under construction and those yet to be funded. A similar trend was observed for the total wastewater flow requiring treatment. These data are summarized in Tables 13 and 14. There are approximately 10,861 wastewater treatment plants currently in use or under construction in the United States. An additional 7,775 treatment facilities will be required between 1978 and 2000 to treat approximately 49 x 10^6 m^3/d (12,974 mgd) of wastewater flow. This represents an average daily flow per facility of approximately 6,320 m^3/d (1.66 mgd). In addition, the Needs Survey data indicate that between 80 to 90 percent of these facilities will be utilizing some form of the activated sludge process. Based on this analysis, it is evident that activated sludge is by far the most prevalent treatment technology, both in terms of the number of facilities and the volume of wastewater flow.

The Deep Shaft biological treatment process utilizes the same principles as the activated sludge process, and, therefore, has the potential to capture a portion of the future treatment needs. The market potential which can be realized by the Deep Shaft technology will depend to a large extent on the development and publication of reliable cost, performance, and energy data.

TABLE 13. WASTEWATER TREATMENT PROCESS PROFILE[1]--
NUMBER OF FACILITIES

Process Category	Now in Use	Under Construction	Required Not Funded
Trickling filter and its modifications	2,863 (28.8)[2]	88 (9.6)	200 (2.6)
Activated sludge and its modifications	6,670 (67.1)	662 (71.9)	6,673 (85.8)
Other(s)[3]	408 (4.1)	170 (18.5)	902 (11.6)
Total	9,941	920	7,775

Source: 1978 Needs Survey

[1]Represents number of wastewater treatment facilities.
[2]Values in parentheses represent percent of total for each category.
[3]Includes rotating biological contactors (RBC), oxidation ditches, etc.

TABLE 14. WASTEWATER TREATMENT PROCESS PROFILE[1]--
FLOW TO BE TREATED

Process Category	Now in Use	Under Construction	Required Not Funded
Trickling filter and its modifications	17,093 (4,484)	1,107 (291)	4,985 (1,315)
% Total	(15.2)	(8.2)	(10.1)
Activated sludge and its modifications	94,313 (24,912)	11,175 (2,950)	39,907 (10,541)
% Total	84.1	82.9	81.2
Other(s)[2]	779 (205)	1,197 (316)	4,237 (1,118)
% Total	0.7	8.9	8.7
Total	112,185 (29,601)	13,479 (3,557)	49,129 (12,974)

Source: 1978 Needs Survey

[1]Represents wastewater flow data in 10^3 m^3/d and mgd (in parentheses).
[2]Includes rotating biological contactors (RBC), oxidation ditches, etc.

In general, because of its design and operating characteristics, the greatest market potential for the Deep Shaft process is for the treatment of high strength wastewaters ($BOD_5 \geq 500$ mg/L). Therefore, there is greater potential for the use of the Deep Shaft process in POTW's treating joint industrial and domestic wastewaters. In addition, the potential for the Deep Shaft process is high at locations where space restrictions prevail as the system requires less space than conventional or high rate activated sludge systems.

COST AND ENERGY IMPACTS

Based on the cost and energy requirements analysis (Tables 7 through 12), no definitive conclusions could be drawn relative to cost or energy savings that can be realized by use of the Deep Shaft process. For the plant capacities used in the cost analysis (1,892-37,850 m^3/d; 0.5 to 10.0 mgd), the installed capital cost estimates for the Deep Shaft process were equivalent ($\pm$ 25%) to the conventional air-activated sludge process as they are within the accuracy of the estimating procedure. The Deep Shaft process showed some savings in installed capital costs over the pure oxygen-activated sludge system for all of the flow ranges for which the comparative analysis was prepared. When the cost comparison is based on present worth value, all three technologies are found to be equivalent. Based on this evaluation, no significant national impacts can be predicted for the Deep Shaft process.

A similar analysis was conducted for the energy requirements of the three technologies (Tables 9 through 11). Based on this analysis, it can be concluded that the unit energy requirements (kWh/1,000 m^3 of wastewater treated) are the highest for the Deep Shaft process when treating domestic wastewaters. The pure oxygen-activated sludge process required the least unit energy for the 1,892 m^3/d (0.5 mgd) plant size because of the use of purchased liquid oxygen. For larger plant capacities (18,925 and 37,850 m^3/d), however, the pure oxygen process required the same unit energy as the conventional air-activated sludge process. This was due to the requirement for additional energy for on-site oxygen generation.

When the energy use comparison was made on the basis of BOD_5 removal (kg BOD_5/kWh), a similar conclusion is reached indicating that the pure oxygen-activated sludge process is favored for the 1,892 m^3/d (0.5 mgd) plant size over the other two technologies. However, when the on-site oxygen generation equipment is incorporated, the energy benefits for the pure oxygen process are nullified.

Based on this analysis, it is evident that the Deep Shaft process benefits (cost and energy) can only be realized when the raw wastewater strength is greater than normal domestic wastewater. This is because the energy requirements for the Deep Shaft process treating domestic wastewaters are based on the requirement for maintaining liquid circulation velocities rather than on the basis of BOD_5 removal. When the raw wastewater BOD_5 concentration is high ($\geq$500 mg/L), the cost and energy savings are likely to be in favor of the Deep Shaft process.

RISK ASSESSMENT

The Deep Shaft biological treatment process is conceptually identical to the conventional air-activated sludge and the pure oxygen-activated sludge processes. A review of the more recent design practices, however, indicates that the Deep Shaft process for domestic wastewater treatment has a nominal detention time between 30 and 60 minutes. This detention time approximates the mean generation time of organisms typically present in the activated sludge. As a result, variations in influent flow rate are likely to shift the population dynamics of the activated sludge culture. In the design of conventional air- and pure oxygen-activated sludge systems utilizing primary gravity sedimentation, a minimum detention time of two hours is utilized to prevent shifts in population dynamics, and to preserve the settling characteristics of the mixed liquor suspended solids. In other words, a minimum detention time of two hours is necessary to maintain the biological integrity of the conventional system. The impact of the lower detention time (30 to 60 min) for the Deep Shaft process and the downstream flotation separator cannot be assessed at this time, and therefore, constitutes a potential risk with respect to the performance of the Deep Shaft process.

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APPENDIX A

COST AND ENERGY ANALYSIS -- ASSUMPTIONS

In order to compare the various alternatives, a basis for the cost comparison was required. The major sources of cost (capital, and operations and maintenance) and energy requirement data were the Innovative and Alternative Technology Assessment Manual (I&A)(1) with additional input from the Areawide Assessment Procedures Manual, Appendix H(33), and Eco Technology.

In order to accommodate the specific design conditions, numerous assumptions were required to adjust and extrapolate cost data which will reflect the specific design case. The assumptions utilized for technology evaluation are as follows:

1. Construction costs were updated to fourth quarter 1980 utilizing the Engineering News Record Index, ENR = 3376.

2. Operation and maintenance costs were updated to fourth quarter 1980 utilizing EPA's Average O&M Index = 3.04.

3. Construction costs were upgraded to capital costs by inclusion of noncomponent costs. The noncomponent costs and the percentage of construction costs used are as follows:

Piping	- 10%
Electrical	- 8%
Instrumentation	- 5%
Site Preparation	- 5%

4. Engineering services and contingency costs were each assumed to be 15% of the capital cost. The sum of the construction costs, noncomponent costs, engineering services, and contingency yielded the total installed capital cost.

5. For the 1872 m^3/d (0.5 mgd) plant size utilizing conventional air (baseline) or pure oxygen (equivalent) activated sludge process to account for differences in the design between the I&A Manual and the work reported herein, the I&A Manual curves were appropriately modified to reflect the following:

   a. The exclusion of the primary clarifier resulted in a higher BOD_5 loading to the activated sludge process (200 mg/L versus 130 mg/L).

   b. Differences in influent feed sludge concentration to the aerobic digester (1 percent vs. 4 percent solids).

6. For all three plant sizes utilizing the Deep Shaft process, the costs obtained from Eco Technology were assumed turnkey, and zero noncomponent, engineering services, and contingency costs were assumed to be associated with the Deep Shaft portion of the total cost.

7. For all three Deep Shaft process designs, modifications to the I&A Manual costs for digestion were required to reflect the concentration of solids obtained from the flotation cell. For the 1,892 m^3/d (0.5 mgd) case, these modifications were made to the aerobic digester curves, whereas for the 18,925 m^3/d (5.0 mgd) and the 37,850 m^3/d (10 mgd) designs, modifications were made to the anaerobic digester curves. These corrections were required to correct for the 7-percent solids produced by the flotation unit.

8. For 18,925 m^3/d (5.0 mgd) and 37,850 m^3/d (10.0 mgd) anaerobic digesters, digester gas was assumed to be combusted in order to heat the primary digester. No cost or energy credit was given for any excess gas.

9. For all nine process and size alternatives, sludge transport by truck, to ultimate disposal, of 6.2 km (10 miles) one way was assumed. Appropriate assumptions as to sludge generation rates and dewatered sludge concentrations were made to allow for sludge volume calculations. Energy requirements were modified from data presented in the I&A Manual.

10. For present worth analysis, all equipment was assumed to have a 20-year service life (zero salvage or replacement cost over cost-effectiveness time period), and present worth was equal to sum of capital cost plus present worth of annual O&M costs.

APPENDIX B

DESIGN DATA AND FACT SHEETS
(Source: Eco Technology)

DEEPSHAFT

1 Technical Profile

Virden Plant

The Town of Virden, Manitoba, Canada, is the site of the first full-scale Deep Shaft plant in North America. The Town of Virden is a petroleum service centre and agricultural community with a population of 5,000 people. The town is located approximately 288 km (180 miles) west of Winnipeg on the Trans-Canada Highway. The plant is designed to treat approximately 2271 m^3 per day (0.6 USMGD) of municipal strength effluent to secondary treatment discharge requirements.

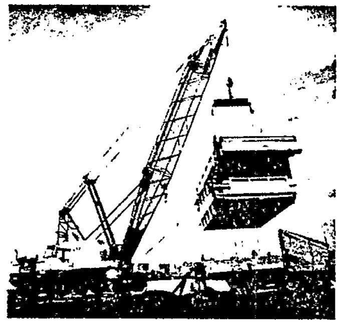
Conventional funding for the project was provided by three levels of government. The Canadian government provided funding through the Canada Mortgage and Housing Corporation (CMHC) and the Prairie Farm Rehabilitation Administration (PFRA). Provincial and Civic funds were obtained from the Manitoba Water Services Board and the Town of Virden.

Reid Crowther & Partners Limited in Winnipeg, Manitoba are principal consulting engineers on the project. Eco-Research Limited provided the Deep Shaft secondary treatment plant on an installed basis at a firm price to the Town of Virden.

The Deep Shaft process was selected because:

- the plant could be built at a lower capital cost than other alternatives,
- the entire facility could be enclosed, an important factor due to −40° C winter ambient temperatures and,
- the Town of Virden received incentives in the form of a firm price for an installed plant coupled with performance and operating cost warrantees.

The plant is totally enclosed in a building requiring approximately 465 m^2 (5,000 ft^2). The process includes coarse screening, a small surge tank, grit removal, Deep Shaft aeration, solids separation by flotation and effluent chlorination. Waste biological solids are thickened in an existing Imhoff tank prior to disposal at an approved sanitary landfill site. The building also includes a control room, laboratory, chlorine room, plus compressor and chemical storage areas. The plant is also equipped with chemical mixing and feed systems to allow the addition of chemical flotation aids if required.

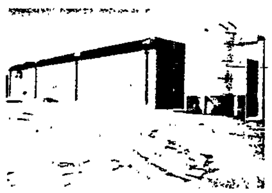


Prefabricated components allowed rapid installation.

Biological aeration is achieved in a single shaft 762 mm in diameter and 153 m deep (30" I.D. × 500'). The shaft is cased with steel and grouted to the geological formation with concrete. Shaft placement was completed in one month using a conventional truck mounted drilling rig.

Three flotation tanks operating in parallel, result in a high quality effluent containing less than 30 mg/l BOD_5 and 30 mg/l TSS. The flotation process concentrates waste activated sludge to 5% which greatly reduces the volume of sludge for disposal.

The Town of Virden Deep Shaft plant was commissioned in early 1980 at a total project cost of approximately $1.3 million (1979 Canadian).



Plant enclosure is economical, practical and aesthetically pleasing.

eco

Design criteria and operating parameters

	Parameter	US Units	SI Units
Deep Shaft bioreactor	Average daily flow (ADF)[a]	0.6 USMGD	2271 m^3/day
	Instantaneous peak flow[b]	1.8 USMGD	6813 m^3/day
	BOD_5 loading at ADF	1000 lb/day	453.5 kg/day
	MLSS	0.8%	8000 mg/l
	MLVSS	0.6%	6000 mg/l
	F/M ratio at ADF[c]	1.06 day^{-1}	1.06 day^{-1}
	Volumetric loading[d]	396.5 lb BOD_5/day/1000 ft^3	6.4 kg BOD_5/day/m^3
	Detention time[e] Nominal Actual	 41 min 35 min	 41 min 35 min
	Sludge retention time[f]	1.9 days	1.9 days
	Aeration Energy	40 hp	30 kW
Flotation clarification	Surface overflow rate[g] (Hydraulic loading)	476 USGPD/ft^2	19.4 m^3/day/m^2
	Mass loading[g]	31.8 lb/day/ft^2	155.3 kg/day/m^2
	Return sludge flow rate Float recycle Sink recycle	 16% Variable	 16% Variable
	Return sludge concentration Float solids Sink solids	 5% Variable	 50,000 mg/l Variable
	Waste activated sludge[h]	425 lb VSS/day 0.69 lb TSS/lb BOD_5 0.5 lb VSS/lb BOD_5	193 kg VSS/day 0.69 kg TSS/kg BOD_5 removed 0.5 kg VSS/kg BOD_5 removed

a Design flow based on a population of 5000 with 120 USGPCD.

b Based on a Harmon formula - peak flow = 3 times average flow.

c F/M ratio assumes an influent BOD_5 concentration of 200 ppm, and a MLVSS content of 75% within the deep shaft and head tank.

d Loading based on head tank and deep shaft volume.

e Actual detention time based on float and sink recycle rates of 16% and 0% respectively.

f SRT defined as kg MLVSS in deep shaft bioreactor and head tank per kg VSS wasted as activated sludge, plus VSS lost in effluent per day.

g Flotation tank loadings based on internal tank dimensions and average daily flow influent rate

h Activated sludge wasted based on average BOD_5 concentrations of 200 ppm and 30 ppm in the influent and effluent, respectively.

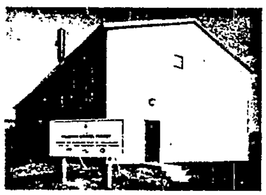
2 Technical Profile

DEEPSHAFT

Ithaca Plant

The Ithaca Deep Shaft Demonstration Plant was assisted by a $500,000 research and development grant from the USEPA Municipal and Environmental Research Laboratory in Cincinnati, Ohio. Stearns & Wheler, Investigating Officers for the USEPA are responsible for supervising plant operations, evaluating the Deep Shaft process for performance and preparing a final report for submission to the USEPA. The City of Ithaca provides qualified operating and analytical personnel to operate the plant during a 64 week evaluation program. Eco-Research assumed responsibility for construction and commissioning of the Deep Shaft Demonstration Plant.

The plant is unique in that two Deep Shaft process flowsheets are integrated into the same plant. The process can be operated in both flotation and sedimentation clarification modes. Emphasis is placed upon operating the plant in the flotation clarification mode at an average daily flow of 757 m^3 per day (200,000 USGPD). The process is designed to produce an effluent containing not greater than 30 mg/l total BOD_5 and 30 mg/l TSS. The plant was commissioned in October, 1979 and operating results confirm that the process produces specification effluent. Consideration is being given to a full scale Deep Shaft plant at the existing site.


Ithaca Deep Shaft plant is totally enclosed.

Biological treatment is performed in a single shaft 136 m (446') deep which is cased its full length with a 438 mm (17.25") I.D. casing grouted to the geological formation with concrete. Solids separation is achieved in a flotation clarifier 3.43 m wide × 10.7 m long and 3.96 m deep (11.25 × 36 × 13 ft). Treated effluent and waste solids


Ithaca flotation cell clarifier driven by dissolved gases of Deep Shaft

are returned to the City of Ithaca's existing secondary effluent treatment plant.

Initial results from Ithaca have confirmed the Deep Shaft as an innovative technology with the potential to significantly reduce life cycle costs and/or energy requirements for publically or industrially owned wastewater treatment plants.

Design criteria and operating parameters

	Parameter	Units	Flotation Clarification mode	Sedimentation Clarification mode
Deep Shaft bioreactor	Nominal design flow	m^3/day USGPD	757 200,000	379 100,000
	MLSS	mg/l	10,000	5,000
	SRT[a]	days	2.1	2.1
	F/M[b]	$days^{-1}$	.74	.74
	Volumetric loading[c]	kg BOD_5/day/m^3 lbs BOD_5/day/1000 ft^3	5.54 346	2.77 173
	Detention time[d]: Nominal Actual	minutes	39 24	78 39
Solids separation unit	Surface overflow rate	m^3/day/m^2 USGPD/ft^2	20.1 494	10.1 247
	Mass loading[e]	kg TSS/day/m^2 lbs TSS/day/ft^2	321 66	103 21
	Return sludge flow rate: Float recycle Sink recycle	% of nominal Design flow	20 40	N/A 100
	Return sludge concentration: Float solids Sink solids	% TSS	7-10 3-4	N/A 1-2
	Waste activated sludge[f]:	lb TSS/day kg TSS/day kg TSS/kg BOD_5 removed kg VSS/kg BOD_5 removed	170 77 .75 .45	85 38.5 .75 .45

a SRT defined as kg MLSS in bioreactor per kg TSS wasted as activated sludge plus loss in the effluent per day

b F/M loading assumes an influent BOD_5 concentration of 150 mg/l and a MLVSS content of 75 per cent.

c Volumetric organic loading estimated assuming an influent BOD_5 of 150 mg/l, a MLVSS content of 75 per cent, a nominal shaft diameter of .44 m (7.25 in), and a shaft depth of 136 m (446 ft).

d Actual detention time based on sludge recycle rates of 100 per cent in the gravity clarification mode and 20 per cent and 40 per cent, respectively, for float solids and bottom solids in the flotation clarification mode.

e Mass loadings are based on total sludge return rates of 60 and 100 per cent and MLSS concentrations of 10,000 and 5,000 mg/l, respectively, in the flotation and gravity clarification modes.

f Activated sludge wasted per unit of BOD_5 removed based on an influent BOD_5 of 150 mg/l and an effluent BOD_5 of 15 mg/L.

DEEP SHAFT

3 Technical Profile

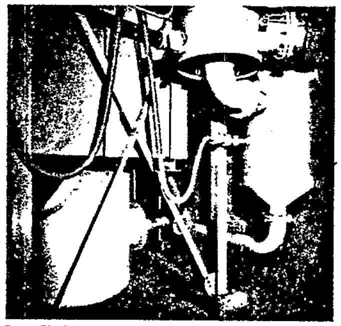
Molson's Brewery Plant

Deep Shaft pilot studies conducted at Molson's Brewery (Ontario) Limited at Barrie, Ontario, Canada from 1976 to 1978, resulted in the construction of a full scale Deep Shaft facility at the same site. The full-scale plant is designed to treat 2,091 m^3 per day (.552 USMGD) of high strength brewery effluent to direct discharge standards of 50 mg/l BOD_5 and 50 mg/l TSS. The average daily organic load to this Deep Shaft plant is 5,000 kg total BOD_5 per day (11,000 lbs BOD_5 per day).

The Deep Shaft plant at Barrie has two 1.37 m O.D. (54") cased bioreactors, each placed to a depth of 153 m (500'). The Deep Shaft is grouted with concrete to the surrounding geological formation. Shaft internals are of multi-channel design which allows influent injection and mixed liquor removal from the shaft at depth.

Brewery effluent is split between an existing extended aeration plant and the new Deep Shaft system. The brewery effluent entering the Deep Shaft plant is screened prior to approximately 8 hours of equalization. Equalized wastewater is neutralized to maintain the pH between 6.5 and 8.5 through the addition of either liquid caustic soda or sulphuric acid. Urea and diammonium phosphate are added prior to neutralization to maintain a BOD, nitrogen, phosphorous ratio of 100:10:2. At a total average flow of 2,091 m^3 per day (.552 USMGD) hydraulic retention time of influent per shaft is approximately 300 minutes. This corresponds to 50 cycles within the shaft before discharge to the flotation tank.

Air is supplied to the two Deep Shafts from three rotary screw compressors located in the brewery power house. Initial operating experience indicates that each train requires approximately 93 kW (125 hp). Air is added to the shafts through injection lines in the downcomer and riser sections.



Deep Shaft headworks showing Holding tank, Swirl tank, and 1.37 m diameter Deep Shaft.

Foam generated in the process is treated in a separate foam tank and then recycled back to the shaft.

Solids separation is achieved utilizing flotation clarification which features air drive created by the air lift in the Deep Shaft.

Waste activated sludge generated in the process, is dewatered by a Tait Andritz belt press located in the Deep Shaft building.

Results confirm that the Deep Shaft produces an effluent containing less than 50 mg/l BOD_5 and 50 mg/l TSS. Initial seeding of the Deep Shaft plant was accomplished utilizing sludge from the existing extended aeration plant. Filamentous organisms have never been observed in the Deep Shaft.

The entire wastewater treatment plant was built at a cost of approximately $3.2 million (1979 Canadian). Partial funding for the project was made possible by a Government of Canada Development and Demonstration of Pollution Abatement Technology (DPAT) grant awarded in 1978.

External view of Deep Shaft plant requiring 625 m^2 (6700 ft^2).

Design criteria and operating parameters

	Parameter	US Units	SI Units
Deep Shaft bioreactor	Average daily flow (ADF)	0.552 USMGD	2091 m^3/day
	BOD_5 loading at ADF [a]	11000 lb/day	5000 kg/day
	SS loading at ADF	5685 lb/day	2584 kg/day
	MLSS	1.1%	11000 mg/l
	MLVSS	0.825%	8250 mg/l
	F/M ratio at ADF [b]	1.3 day^{-1}	1.3 day^{-1}
	Volumetric loading[c]	652.7 lb BOD_5/day/1000 ft^3	10.5 kg BOD_5/day/m^3
	Detention time[d]		
	Nominal	300 min	300 min
	Actual	256 min	256 min
	Sludge retention time[e]	1.6 days	1.6 days
	Aeration Energy	250 hp	186 kw
Flotation clarification	Surface overflow rate[f] (Hydraulic loading)	431.3 USGPD/ft^2	17.5 m^3/day/m^2
	Mass loading[f]	39.5 lb/day/ft^2	192.9 kg/day/m^2
	Return sludge flow rate		
	Float recycle	17%	17%
	Sink recycle	Variable	Variable
	Return sludge concentration		
	Float solids	4%	40,000 mg/l
	Sink solids	Variable	Variable
	Waste activated sludge[g]	5397 lb VSS/day 0.69 lb TSS/lb BOD_5 0.5 lb VSS/lb BOD_5	2448 kg VSS/day 0.69 kg TSS/kg BOD_5 removed 0.5 kg VSS/kg BOD_5 removed

days. Total BOD_5 is never to exceed 16,500 lbs (7500 kg) per day.

b F/M loading assumes an influent BOD_5 concentration of 2400 ppm, and a MLVSS content of 75% within the Deep Shaft and head tank.

c Loading based on head tank and Deep Shaft volume.

d Actual detection time based on float and sink recycle rates if 17% and 0% respectively.

e SRT defined as kg MLVSS in deep shaft bioreactor and head tank per kg VSS wasted as activated sludge, plus VSS lost in effluent per day.

f Flotation tank loadings based on internal tank dimensions and average influent flow rate.

g Activated sludge wasted based on average BOD_5 concentrations of 2400 ppm and 50 ppm in the influent and effluent, respectively.

4 Technical Profile

DEEP SHAFT

Portage la Prairie Plant

The City of Portage la Prairie is a community of 14,000 people located 80 km (50 miles) west of Winnipeg, Manitoba, Canada on the Trans-Canada Highway. The City of Portage la Prairie Deep Shaft effluent treatment plant will be commissioned in 1981. This advanced Deep Shaft wastewater treatment plant is designed to treat combined food processing effluent and municipal sewage. The population equivalent of the combined waste streams is equal to a municipality of 65,000 people.

W.L. Wardrop & Associates of Winnipeg, Manitoba are the principal consulting engineers on the project. Eco-Research Limited is responsible for the design and installation of the Deep Shaft secondary treatment plant. Northward Project Control Limited, a subsidiary of W.L. Wardrop & Associates is responsible for construction management on the project.

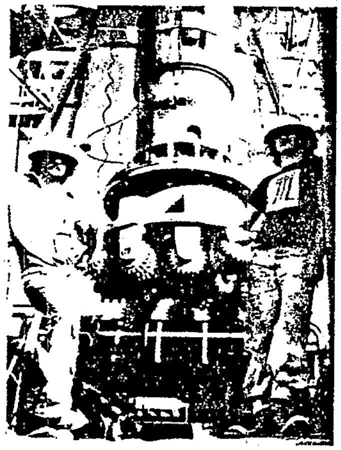
The Deep Shaft plant features dual shafts, each 1.37 m I.D. (54" I.D.) and 137 m (450') deep. Solids separation is achieved utilizing eight flotation clarifiers.

The entire facility is enclosed indoors in approximately 1,115 m^2 (12,000 ft^2).

The plant is capable of treating 5,443 kg BOD_5 per day (12,000 lbs BOD_5 per day) at an average daily flow of 13,625 m^3 per day (3.6 USMGD). Sustained wet weather flow conditions for six weeks in the spring of each year require that the Deep Shaft plant produce an effluent with less than 30 mg/l BOD_5 and 30 mg/l TSS at a flow of 36,333 m^3 per day (9.66 USMGD).

The Deep Shaft process was selected for the City of Portage la Prairie because:

- the process demonstrated large energy savings when compared to other alternatives,
- the Deep Shaft plant is a totally new facility while other alternatives required retrofitting of the existing facility,
- the Deep Shaft plant is totally enclosed which provides an excellent working and treatment environment in view of the harsh Canadian winters and
- the major portion of the project was available at a firm price accompanied by performance and operating cost warranties



Portage big hole drilling tool.

Funding for the project was made possible by Canada Mortgage and Housing Corporation (CMHC), Manitoba Water Services Board, and the City of Portage la Prairie.

The total project cost is estimated at $4 million (1980 Canadian)

Design criteria and operating parameters

	Parameter	US Units	SI Units
Deep Shaft bioreactor	Average daily flow (ADF)	3.6 USMGD	13625 m^3/day
	Peak diurnal flow	7.2 USMGD	27250 m^3/day
	Sustained wet weather flow	9.6 USMGD	36333 m^3/day
	Instantaneous peak flow	14.4 USMGD	54450 m^3/day
	BOD_5 loading at ADF[a]	12000 lb/day	5440 kg/day
	SS loading at ADF	12000 lb/day	5440 kg/day
	MLSS	1.0%	10000 mg/l
	MLVSS	0.8%	8000 mg/l
	F/M ratio at ADF[b]	1.53 day^{-1}	1.53 day^{-1}
	Volumetric loading[c]	762 lb BOD_5/day/1000 ft^3	12.2 kg BOD_5/day/m^3
	Detention time Nominal Actual[d]	 40 min 36 min	 40 min 36 min
	Sludge retention time[e]	1.3 days	1.3 days
	Aeration Energy	150 hp	112 kW
Flotation clarification	Surface overflow rate[f] (Hydraulic loading)	560 USGPD/ft^2	23 m^3/day/m^2
	Mass loading[f]	49.4 lb/day/ft^2	241 kg/day/m^2
	Return sludge flow rate Float recycle Sink recycle	 10% 0% ADF	 10% 0% ADF
	Return sludge concentration Float solids Sink solids	 5% Variable	 50,000 mg/l Variable
	Waste activated sludge[g]	5563 lb VSS/day 0.69 lb TSS/lb BOD_5 0.5 lb VSS/lb BOD_5	2523 kg VSS/day 0.69 kg TSS/kg BOD_5 removed 0.5 kg VSS/kg BOD_5 removed

a For ADF, during sustained wet weather flow BOD_5 concentration cannot exced 20,000 lb/day.
b F/M loading assumes an influent BOD_5 concentration of 400 ppm and a MLVSS content of 75% within the deep shaft and head tank.
c Loading based on head tank and bioreactor volume.
d Actual detection time based on float and sink recycle rates of 10% and 0% respectively
e SRT defined as kg MLVSS in deep shaft bioreactor and head tank per kg VSS wasted as activated sludge, plus VSS lost in effluent per day.
f Flotation tank loadings based on internal tank dimensions and ADF influent rate
g Activated sludge wasted based on average BOD_5 concentrations of 400 ppm and 30 ppm in the influent and effluent respectively.

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