832R92007

U.S. Environmental Protection Agency
Office of Water Enforcement and Compliance
Washington, D.C. 20460

TECHNICAL EVALUATION OF THE VERTICAL LOOP REACTOR PROCESS TECHNOLOGY

SEPTEMBER 1992

NOTICE

ACKNOWLEDGEMENTS

This report was prepared for the U.S. Environmental Protection Agency by J.M. Smith and Associates, Consulting Engineers under subcontract to HydroQual, Inc. HydroQual, Inc. personnel assisted in preparation and review of the report. Mr. Charles Vanderlyn of the Office of Water, Office of Wastewater Enforcement and Compliance, Municipal Technology Branch, was the Project Officer on this contract. Ms. Wendy Bell was the Work Assignment Manager for the study.

CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

BACKGROUND AND OBJECTIVES

The EPA encourages the utilization of more efficient wastewater treatment techniques by supporting the evaluation of new technologies. The EPA technology transfer programs are designed to allow the development and application of new and significant technologies before there is a chance for extensive field evaluation. The EPA will also discourage certain technologies or specific applications of certain technologies if the available information indicates crucial limitations.

The primary objective in the evaluation of specific technologies is to verify performance claims by process or equipment developers or manufacturers. Technology evaluations may identify specific weaknesses or limitations in terms of performance, cost, operation or maintenance. In addition, the results of the evaluation may specify a range of conditions under which the technologies are not as effective as the developers claim.

Conversely, other technologies may show good promise. In these cases, the EPA is interested in introducing the new technologies to the public. The EPA also wishes to provide the wastewater treatment community with all the available information regarding new technologies which exhibit advantages over conventional methods. Whether the evaluation finds the developer's or manufacturer's claims accurate or misleading, the EPA recognizes the need to examine and document significant new technologies.

TECHNOLOGY DESCRIPTION

A vertical loop reactor (VLR) is an aerobic suspended growth activated sludge biological treatment process similar to an oxidation ditch. The wastewater in an oxidation ditch circulates in a horizontal loop; the water in a VLR circulates in a vertical loop around a horizontal divider baffle. A VLR consists of a concrete or steel basin with a horizontal baffle extending the entire width of the reactor and most of its length.

Currently, there is only one VLR manufacturer, Envirex Inc. Envirex claims that the oxygen requirements for a VLR system are lower than the requirements for an equivalent conventional oxidation ditch system. These claims are primarily based on the location of the diffusers in the VLR and on the nitrate derived oxygen returned to the biomass by denitrification.

FINDINGS AND CONCLUSIONS

The following summarizes the major findings and conclusions of this evaluation of VLRs. The information contained herein is based on analysis of available information from site visits, a detailed design of a full scale VLR system by the report authors, information from consultants, VLR and oxidation ditch manufacturers.

1. The VLR is a modification of the conventional activated sludge process. The unique features of the process are circulating mixed liquor around a horizontal baffle with a dual aeration system of course bubble diffused air beneath the horizontal baffle and disc aerators at the surface of the aeration tank. The process operates as a plug flow reactor with capability for varying dissolved oxygen profiles to achieve biological phosphorus and nitrogen removal. The VLR process also features a stormwater by-pass design for treatment of high peak to average flows.

2. There are currently seven operating VLRs in the U.S. ranging in size from 0.22 to 4.5 mgd. Three additional plants ranging in size from 3.0 to 5.0 mgd are in the design phase.

3. Performance data from operating VLRs show that this process is capable of achieving effluent carbonaceous biochemical oxygen demand (CBOD) levels of less than 10 mg/l; effluent total suspended solids (TSS) levels of less than 10 mg/l; and effluent ammonia-nitrogen levels of less than 1.0 mg/l. The process is further capable of achieving total nitrogen and phosphorus removals of 60 to 80 percent.

4. The VLR process is applicable for flows ranging from 0.05 to over 10 mgd.

5. The claimed advantages of this process by the manufacturer include the following:

    a. Higher dissolved oxygen transfer than conventional equivalent technology.

    b. Improved response to peak flows due to a stormwater by-pass feature.

c. A credit for oxygen release due to denitrification with the credit based on 80 percent denitrification.

d. Increased mixed liquor settleability and process stability.

6. The design criteria for the existing VLRs are conservative. HRTs range from 11.9 to 24 hours. Volumetric loading ranged from 13.6 to 23.1 lbs of CBOD per 1000 cubic feet. This loading is similar to that used for extended aeration systems and is about 1/3 to 1/2 of that normally used for conventional activated sludge designs.

7. The VLR technology has been designated as Innovative Technology by the EPA for three plants due to a 20 percent claimed energy savings.

8. Based on this assessment, the 20 percent energy savings over competing technology could not be verified.

9. The VLR was compared to oxidation ditches as "Equivalent Technology." The results of this comparison indicated:

   a. The VLR technology produces comparable to slightly improved effluent levels of BOD,TSS and NH_3-N than oxidation ditch plants.

   b. Total removal of phosphorus and total nitrogen are equivalent to oxidation ditches designed for the same level of treatment.

   c. The energy requirements for aeration were found to be similar to 10 percent less than for oxidation ditches.

   d. The land area required for VLRs were found to be approximately 40 percent less than for oxidation ditches based on equivalent aeration tank loadings.

   e. The VLR aeration basin cost was found to be approximately 30 percent less than for oxidation ditches for situations where rock excavation is not required for the deeper VLR basin.

   f. A definitive comparison of total VLR plant costs to total oxidation plant costs could not be made. Data submitted from both manufacturer's indicated a comparable cost for plants in the 0 - 2 mgd range. The reported VLR cost at plants ranging from 2 to 10

mgd were significantly less than oxidation ditch plant costs. This would be expected because of the modular design and common wall construction of the VLR compared to oxidation ditches.

g. The total operation and maintenance costs of the two technologies were found to be similar.

VERTICAL LOOP REACTOR FACT SHEET

Description - A vertical loop reactor (VLR) is a patented activated sludge biological treatment process similar to an oxidation ditch. The wastewater in an oxidation ditch circulates in a horizontal loop; the water in a VLR circulates in a vertical loop around a horizontal baffle. A typical VLR consists of an 18 foot deep concrete or steel basin with a horizontal baffle extending the entire width of the reactor and most of its length. Because a VLR is typically deeper than an oxidation ditch, the VLR requires less land area.

Aeration in a VLR is provided by coarse bubble diffusers, which are located below the horizontal baffle and by disc aeration mixers. The disc mixers also circulate the wastewater around the baffle. Because the diffusers are positioned below the baffle, the air bubble residence time in a VLR is as much as six times longer than the bubble residence time in a conventional aeration system. The manufacturer claims this increases process aeration efficiency. Denitrification in an anoxic zone also reduces oxygen requirements.

The VLR process is usually preceded by preliminary treatment such as screening, communition or grit removal. Secondary settling of the VLR effluent is typically provided by a separate clarifier.

Common Modifications - An intrachannel clarifier may be used for secondary settling in place of a separate clarifier. Vertical loop reactors may be operated in parallel or series. When a series of VLRs are used, the dissolved oxygen profile can be controlled to provide nitrification, denitrification and biological phosphorus removal at hydraulic detention times of 10 to 15 hours.

Technology Status - There are currently (June 1991) six municipal wastewater treatment facilities in the United States with the VLRs. There are also at least four VLR systems in the United States currently in the design and construction stages.

Typical Equipment/Number of Manufacturers - The VLR is a patented process of the Envirex Corporation (one manufacturer). Disc aeration mixer/1; coarse bubble diffusers/>10,

Applications - VLR technology is applicable in any situation where conventional or extended aeration activated sludge treatment is appropriate. The technology is applicable for nitrification and denitrification. Biological phosphorus removal may be incorporated in the system design. Power costs may be lower for a VLR system than for other aerated biological treatment systems, due to improved oxygen transfer efficiency.

Limitations - Limited operating information is available and there appears to be a lack of understanding on the part of both designers and operators concerning the applicability and flexibility of the process for nutrient removal.

Performance - The average effluent BOD and TSS concentrations for five operating VLR facilities are 4.2 and 7.1 mg/l, respectively. The average effluent ammonia concentration is 0.8 mg/l (based on data from four plants). Only one of the VLRs studied was designed for biological phosphorus removal; the average effluent phosphorus concentration for this plant was 1.45 mg/l and alum was added in the final clarifiers. A second VLR facility was not designed for biological phosphorus removal but was required to monitor phosphorus. This plant had an average effluent phosphorus concentration of 2.19 without any chemical addition.

Chemicals Required - None.

Residuals Generated - Secondary sludge is generated at quantities similar to the activated sludge process depending on the system operation conditions (SRT and organic load).

Design Criteria - BOD loading: 13.6 to 22.0 BOD/1,000 ft^3/day
SRT: 17.0 to 36.5 days
Detention Time: 11.9 to 24.0 hours

Unit Process Reliability - The following table indicates the percent of time the monthly average effluent concentration of the given pollutants was less than the concentration given in the first column. This table was developed from the data discussed in the performance section of this sheet, although some start-up data were eliminated. No significant difference in results were observed between winter and summer data.

	Percentage of Monthly Average Concentration			
Concentration (mg/L)	BOD	NH_3-N	TSS	P
0.2	0	30	0	2
0.5	0	65	1	10
1.0	0	83	1	24
2.0	20	88	5	65
5.0	71	95	43	93
10.0	97	96	75	100
20.0	100	100	96	100
Plants	5	5	5	1

Environmental Impact - Solid waste, odor and air pollution impacts are similar to those encountered with standard activated sludge processes.

Toxic Management - The same potential for sludge contamination, upsets and pass-through of toxic pollutants exists for VLR systems as standard activated sludge process.

Energy Notes

Energy requirements are based on the following assumptions:

Water Quality	Influent	Effluent
BOD_5	200	20
TKN	35	1

Design Basis

Oxygen transfer efficiency = 2.5 lb O_2/Hp hour
Nitrification occurs

Operating Parameters -

Oxygen Requirement	1.5 lb O_2/lb BOD_5 removed
	4.57 lb O_2/lb TKN oxidized

Type of Energy - Electrical

Costs

Construction Costs - Very limited data available. Only a few plants, some of which are retrofits, have been built.Construction costs (March 1991 dollars) supplied by manufacturer are shown. Costs are for VLR only.

Operation Costs - Similar to oxidation ditch type treatment plant.

Reference

Technical Evaluation of the Verticle Loop Reactor Process Technology, J.M. Smith & Associates, USEPA, November 1991.

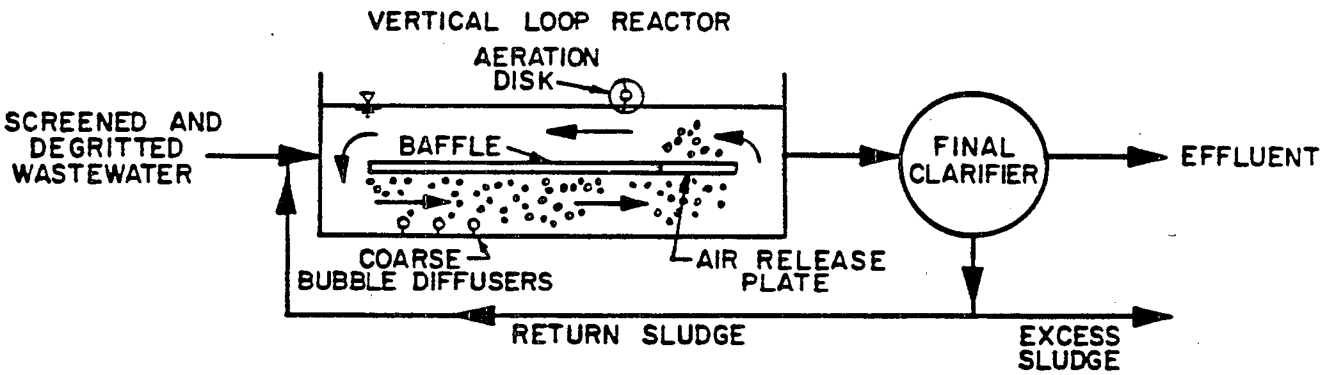

Figure FS-1
Flow Diagram

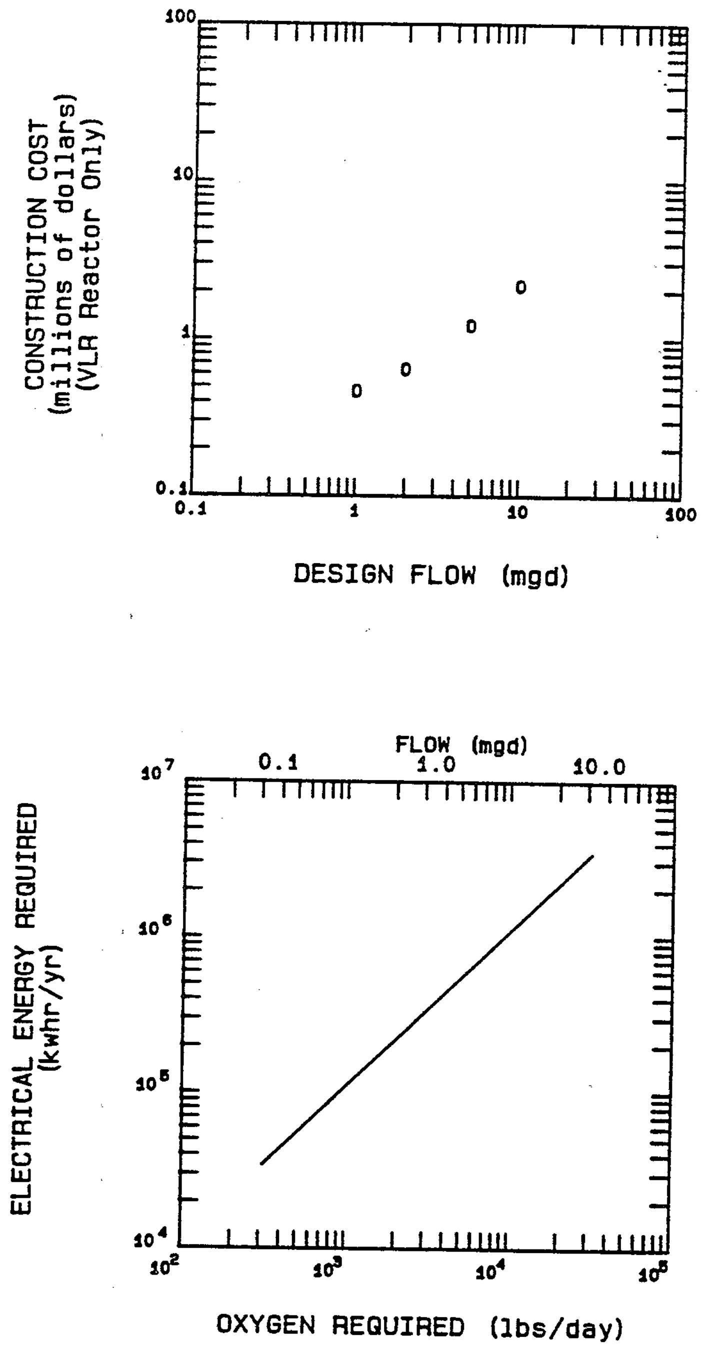

Figure FS-2
Construction Costs and Electrical Energy

SECTION 1
INTRODUCTION

BACKGROUND AND OBJECTIVES

The EPA encourages the utilization of more efficient wastewater treatment techniques by supporting the evaluation of new technologies. The EPA technology transfer programs are designed to allow the development and application of new and significant technologies before there is a chance for extensive field evaluation. The EPA will also discourage certain technologies or specific applications of certain technologies if the available information indicates crucial limitations.

The primary objective in the evaluation of specific technologies is to verify performance claims by process or equipment developers or manufacturers. Technology evaluations may identify specific weaknesses or limitations in terms of performance, cost, operation or maintenance. In addition, the results of the evaluation may specify a range of conditions under which the technologies are not as effective as the developers claim.

Conversely, other technologies may show good promise. In these cases, the EPA is interested in introducing the new technologies to the public. The EPA also wishes to provide the wastewater treatment community with all the available information regarding new technologies which exhibit advantages over conventional methods. Whether the evaluation finds the developer's or manufacturer's claims accurate or misleading, the EPA recognizes the need to examine and document significant new technologies.

TECHNOLOGY DESCRIPTION

A vertical loop reactor (VLR) is an aerobic suspended growth activated sludge biological treatment process similar to an oxidation ditch. The wastewater in an oxidation ditch circulates in a horizontal loop; the water in a VLR circulates in a vertical loop around a horizontal divider baffle, as shown in Figure 1. Figure 1 also illustrates the basic reactor configuration for a VLR.[1] A VLR consists of a concrete or steel basin with a horizontal baffle extending the entire width of the reactor and most of its length.

Existing VLR basins have side-wall depths which range from approximately ten to twenty-two feet.[2] The length and width of the VLR are determined by the required capacity but, as a rule, the length is at least twice the width. The

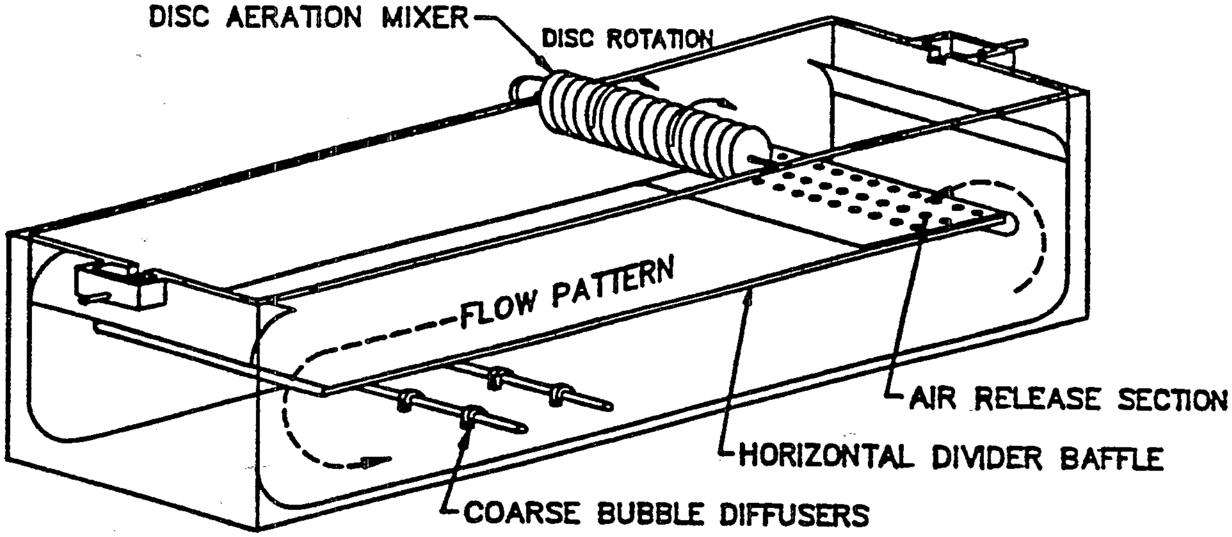

Figure 1
Basic Reactor Configuration

baffle is generally five to eleven feet below the surface of the water. Existing tanks or basins may be retrofitted to serve as VLRs.

Standard VLRs utilize disc aeration mixers to provide continuous circulation of the wastewater at a velocity of 1.0 to 1.5 feet per second.[3] Submersible mixers are also available and may be used in place of the disc aeration mixers. When the aeration disc mixers are used, they are the primary source of aeration at low loadings because the amount of aeration provided by the discs is not easily adjustable.

Coarse bubble diffusers near the bottom of the reactor provide additional aeration and may be the primary source of oxygen at maximum flow rates or loadings. The amount of oxygen supplied by the diffusers is easily adjustable, so it is usually decreased when the flow rates or loadings are low. The basic reactor configuration shown in Figure 1 illustrates the locations of all major aeration system components.

An air release plate is fastened to the horizontal baffle, as shown in Figure 2. The holes in this plate serve to break up the air bubbles from the diffusers and, according to the manufacturer's claims, improve the oxygen transfer efficiency. VLR systems frequently consist of more than one VLR. In these cases, the reactors may be configured in series or in parallel. Series and parallel configurations are discussed in Section 3 and are illustrated on Figures 3 and 4, respectively.

The VLR process is usually preceded by some type of preliminary treatment such as screening, comminution or grit removal. Secondary settling of the VLR effluent is typically provided by a separate clarifier, although intrachannel clarifiers are available. A typical flow scheme is shown on Figure 5.

Major Process Claims

Currently, the only VLR manufacturer (Envirex Inc.) claims that the oxygen requirements for a VLR system are lower than the requirements for an equivalent conventional system. These claims are primarily based on the location of the diffusers in the VLR and on the nitrate derived oxygen returned to the biomass by denitrification. Oxygen requirements are discussed in detail in Section 3.

The VLR manufacturer states that because the diffusers are positioned below the baffle, the air bubble residence time is as much as six times longer in a VLR than in a conventional aeration system, producing an improved process aeration efficiency.[4]

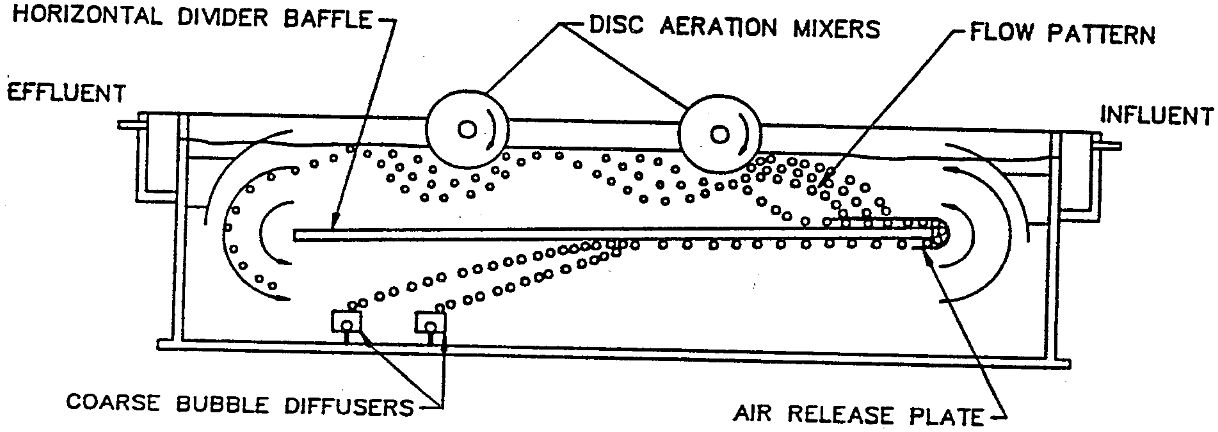

Figure 2
Air Bubble Flow Pattern

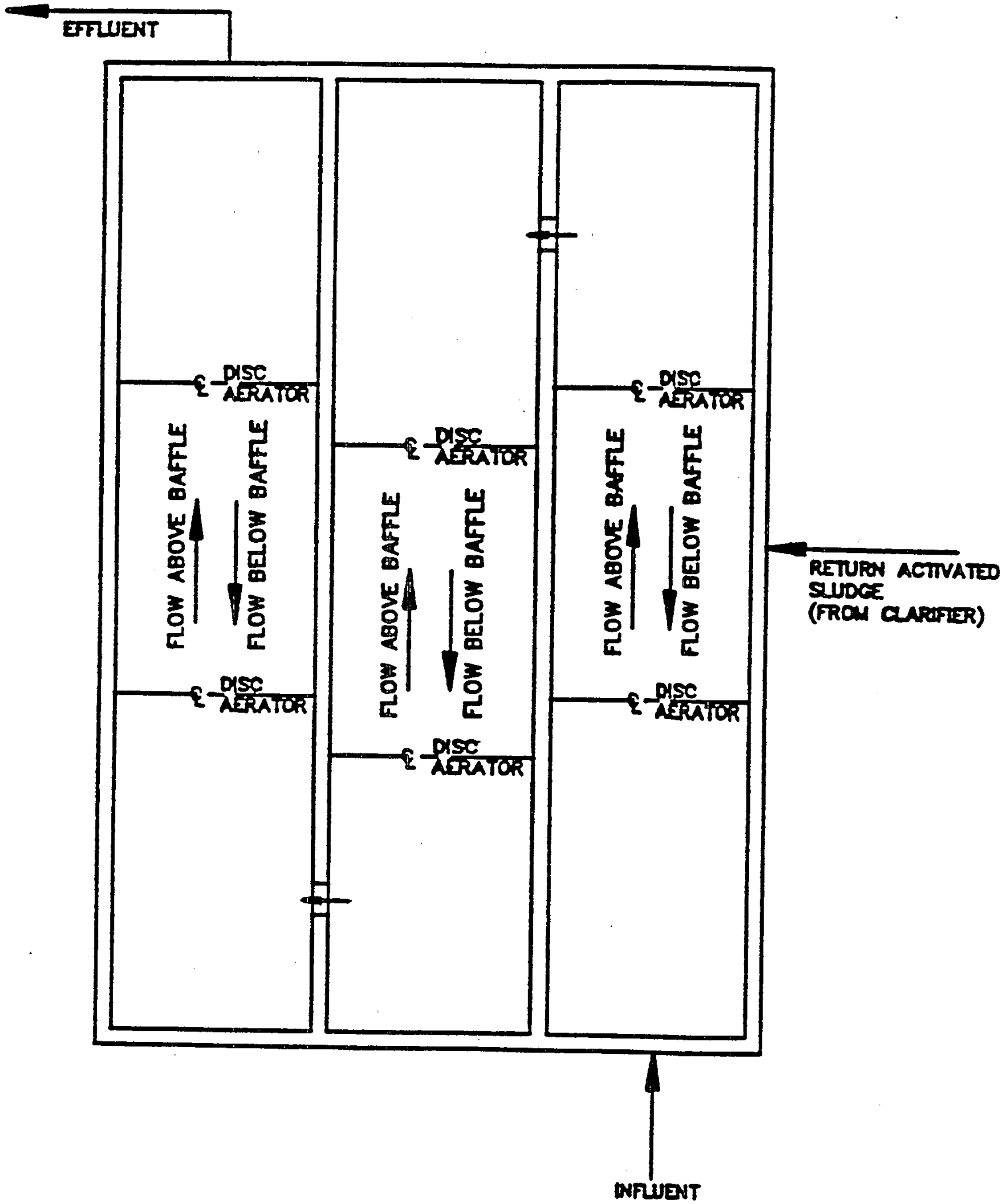

Figure 3
Flow Pattern and Configuration for Vertical Loop Reactors in Series

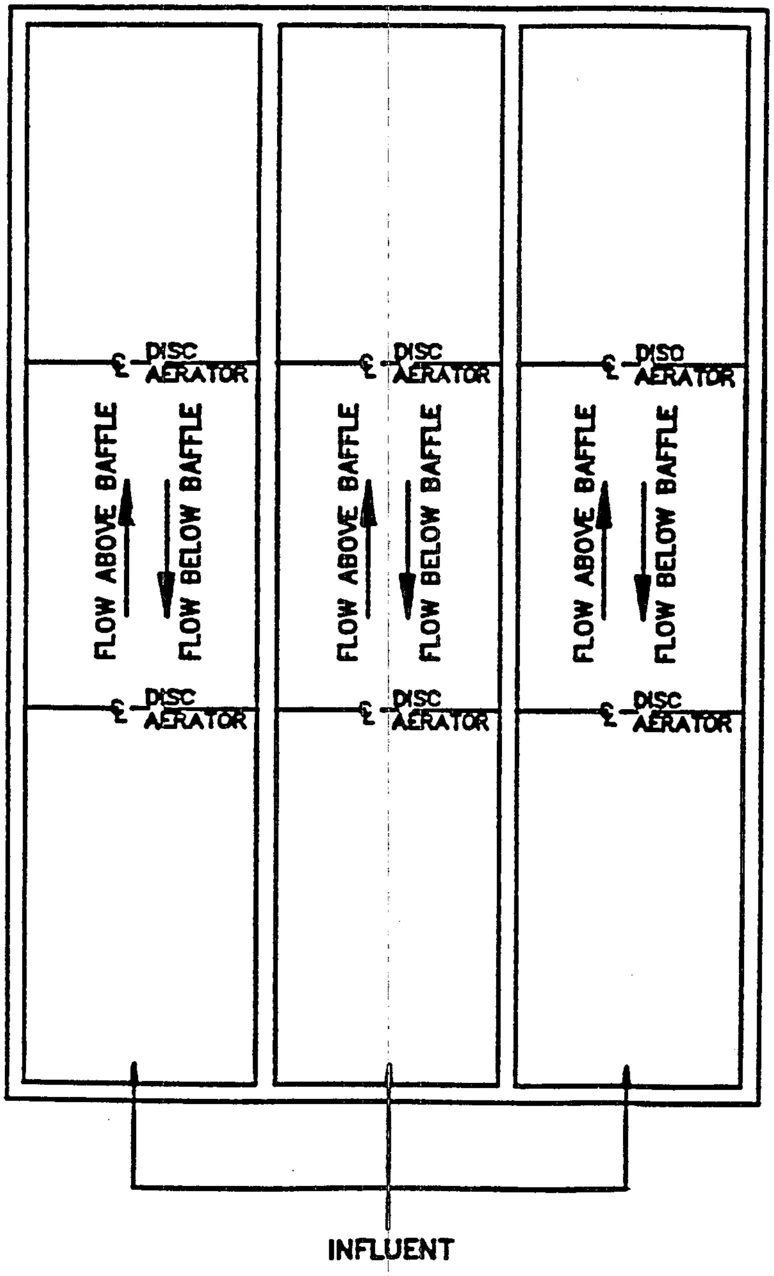

Figure 4
Flow Pattern and Configuration for Vertical Loop Reactors in Parallel

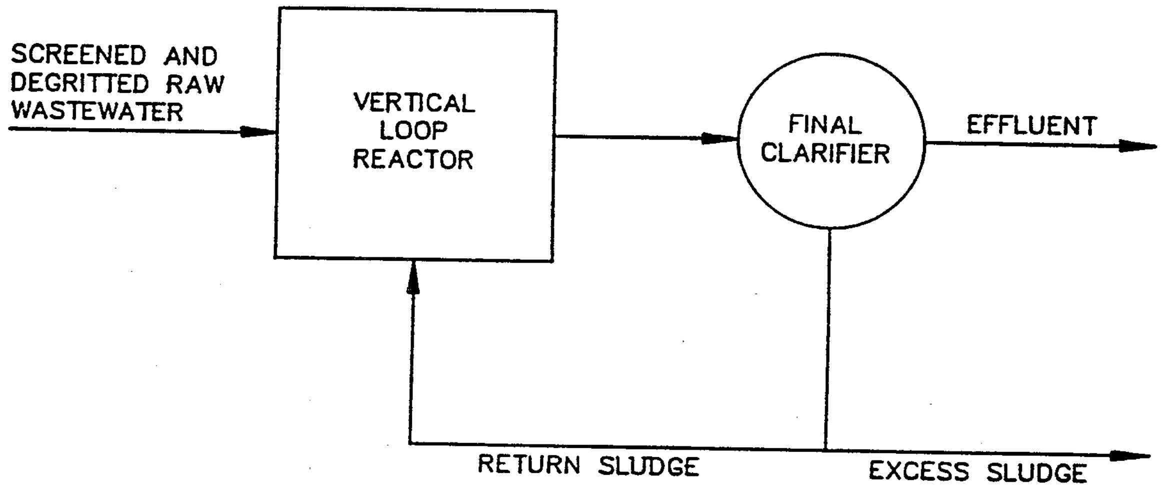

Figure 5
Vertical Loop Reactor Flow Diagram

The VLR manufacturer also claims an oxygen credit for the oxygen released when nitrates and nitrites are reduced to nitrogen gas during denitrification. In a system designed for complete denitrification, this credit would be equivalent to 63 percent of the oxygen required for nitrification. The calculation of the oxygen credit is typically based on no more than 80 percent denitrification. This topic is discussed further in Section 3.

VLRs are frequently designed to provide nitrification and BOD reduction; some are designed for biological denitrification and phosphorus removal, as well. The manufacturer states that VLRs can be designed to allow nitrification, denitrification and BOD removal to occur simultaneously.[4] The biological concepts of particular importance in VLRs and similar systems are discussed in Section 3.

The final major claim made by the manufacturer involves the VLRs ability to treat excessive flows without solids washout. VLR systems can be designed with a stormwater bypass feature, which is described further in Section 3.

FINDINGS AND CONCLUSIONS

The following summarizes the major findings and conclusions of this evaluation of VLRs. The information contained herein is based on analysis of available information from site visits, a detailed design of a full scale VLR system by the report authors, information from consultants, VLR and oxidation ditch manufacturers.

1. The VLR is a modification of the conventional activated sludge process. The unique features of the process are circulating mixed liquor around a horizontal baffle with a dual aeration system of course bubble diffused air beneath the horizontal baffle and disc aerators at the surface of the aeration tank. The process operates as a plug flow reactor with capability for varying dissolved oxygen profiles to achieve biological phosphorus and nitrogen removal. The VLR process also features a stormwater by-pass design for treatment of high peak to average flows.

2. There are currently seven operating VLRs in the U.S. ranging in size from 0.22 to 4.5 mgd. Three additional plants ranging in size from 3.0 to 5.0 mgd are in the design phase.

3. Performance data from operating VLRs show that this process is capable of achieving effluent carbonaceous biochemical oxygen demand (CBOD)

levels of less than 10 mg/l; effluent total suspended solids (TSS) levels of less than 10 mg/l, and effluent ammonia-nitrogen levels of less than 1.0 mg/l. The process is further capable of achieving total nitrogen and phosphorus removals of 60 to 80 percent.

4. The VLR process is applicable for flows ranging from 0.05 to over 10 mgd.

5. The claimed advantages of this process by the manufacturer include the following:

   a. Higher dissolved oxygen transfer than conventional equivalent technology.

   b. Improved response to peak flows due to a stormwater by-pass feature.

   c. A credit for oxygen release due to denitrification with the credit based on 80 percent denitrification.

   d. Increased mixed liquor settleability and process stability.

6. The design criteria for the existing VLRs are conservative. HRTs range from 11.9 to 24 hours. Volumetric loading ranged from 13.6 to 23.1 lbs of CBOD per 1,000 cubic feet. This loading is similar to that used for extended aeration systems and is about 1/3 to 1/2 of that normally used for conventional activated sludge designs.

7. The VLR technology has been designated as Innovative Technology by the EPA for three plants due to a 20 percent claimed energy savings.

8. Based on this assessment, the 20 percent energy savings over competing technology could not be verified.

9. The VLR was compared to oxidation ditches as "Equivalent Technology." The results of this comparison indicated:

   a. The VLR technology produces comparable to slightly improved effluent levels of BOD,TSS and NH_3-N than oxidation ditch plants.

b. Total removal of phosphorus and total nitrogen are equivalent to oxidation ditches designed for the same level of treatment.

c. The energy requirements for aeration were found to be similar to 10 percent less than for oxidation ditches.

d. The land area required for VLRs were found to be approximately 40 percent less than for oxidation ditches based on equivalent aeration tank loadings.

e. The VLR aeration basin cost was found to be approximately 30 percent less than for oxidation ditches for situations where rock excavation is not required for the deeper VLR basin.

f. A definitive comparison of total VLR plant costs to total oxidation plant costs could not be made. Data submitted from both manufacturer's indicated a comparable cost for plants in the 0 to 2 mgd range. The reported VLR cost at plants ranging from 2 to 10 mgd were significantly less than oxidation ditch plant costs. This would be expected because of the modular design and common wall construction of the VLR compared to oxidation ditches.

g. The total operation and maintenance costs of the two technologies were found to be similar.

REFERENCES

1. Brandt, R.A., E.J. Brown, and G.B. Shaw. Innovative Retrofit without Federal Funds: Brookville, Ohio Wastewater Treatment Facilities. Presented at the 63rd Annual Meeting of the Ohio Wastewater Pollution Control Association, June 16, 1989.

2. Miscellaneous information provided by Envirex regarding design criteria, budget costs, etc.

3. Huibrestse, G.L., G.W. Smith, D.J. Thiel, and J.W. Wittmann. Introduction to the Vertical Loop Reactor Process. June 12, 1986.

4. Telephone conversations and correspondence with George Smith of Envirex during March, April, May and June of 1991.

SECTION 2
TECHNOLOGY DEVELOPMENT

HISTORY

The VLR was developed by Mr. George Smith, who is currently employed by the VLR manufacturer. Portions of the VLR technology were derived from the Orbal process, an oxidation ditch also marketed by the VLR manufacturer.

Large-scale pilot testing of the VLR technology began in December, 1983 at a wastewater treatment plant in Walworth County, Wisconsin. An existing plug-flow basin was retrofitted as a VLR and clean-water oxygen transfer tests were conducted by an independent tester and by the VLR manufacturer. The manufacturer states that the clean water aeration efficiency (AE) of the coarse bubble diffusers below the baffle was found to be over 4 lbs. O_2/HP-hr.[1]

TECHNOLOGY STATUS

There are currently seven operating municipal wastewater treatment plants which employ the VLR technology. There is also a pretreatment facility which utilizes a VLR to treat a high-strength industrial wastewater. Industrial treatment will not be discussed further in this report. Locations, start-up dates, and capacities for existing VLR facilities are shown in Table 1.[2,3] The VLR system in Ellijay, Georgia mentioned in Table 1 is not actually in operation for reasons discussed below. Table 1 also includes a partial list of VLR systems which are currently in the design and construction phases.

TABLE 1
LIST OF EXISTING VERTICAL LOOP REACTORS
(NOVEMBER 1991)

Plant Location	Design Flow, mgd	Start-up Date
IN OPERATION:		
Hohenwald, Tennessee	1.1	July 1987
Brookfield, Ohio	1.3	November 1987
Fries, Virginia	0.22	January 1988
Brookville, Ohio	0.645	August 1988
Hillsboro, Ohio	0.85	May 1989
Industrial	0.08	February 1990
Ellijay, Georgia	1.0	January 1991
Willard, Ohio	4.5	April 1991
IN DESIGN/CONSTRUCTION PHASE:		
Hurricane, West Virginia	3.0	
Winchester, Tennessee	5.0	
Warren County, Ohio	3.64	
Wellston, Ohio		

Design criteria for all operating municipal VLRs as well as several VLRs which are under construction was obtained from the manufacturer or from the design engineers and is provided in Table 2.[2,3,4,5] Brief descriptions of six operating VLRs follows.

Hohenwald, Tennessee: The first VLR to begin operation is located in Hohenwald, Tennessee. The design flow rate is 1.1 mgd and the system consists of three reactors in series. The first basin is 20'W x 141.83'L x 16' SWD; the second and third basins are 10'W x 141.83'L x 16'SWD. The manufacturer states that four 10 horsepower disc aerators provide the majority of the oxygen, since the coarse bubble diffusers are not usually needed.

The operating data for this plant indicates an average flow rate of approximately 0.5 mgd, or less than half of the design flow rate. Under these circumstances, it is not surprising that the system usually has no problem meeting its permit limits.[6] Average monthly operating data for the Hohenwald WWTP since the startup of the VLR system can be found in Section 4.

Brookfield, Ohio: The second VLR was installed at the Brookfield (Trumbull County), Ohio WWTP. The design flow was 1.3 mgd; average flow rates for 1988 and 1989 were 1.283 mgd and 1.654 mgd, respectively. The Brookfield system consists of three reactors in series and is equipped with a stormwater bypass. The first basin is 20'W x 128.79'L x 19.75'SWD; the next two reactors are 10'W x 128.79'L x 19.75'SWD. Aeration is provided by four 15 HP disc aerators as well as by coarse bubble diffusers. The Brookfield plant has demonstrated excellent performance for a 30 month period. Effluent BOD, TSS and TKN have averaged 1.6, 3.0 and 1.55 mg/l respectively compared to a permit level of 10 mg/l BOD, 12 mg/l TSS and a summertime/wintertime ammonia-nitrogen limit of 1.5/3.0 mg/l.

Fries, Virginia: The VLR in Fries, Virginia is the smallest in operation. The design flow is low (0.22 mgd) and the plant is underloaded. Only one of the two parallel 20'W x 62'L x 12' SWD basins is used. Each reactor has one 10 HP disc aerator but the manufacturer reports that the aerator in the operating basin is only operated at a power draw of 6.4 wire HP (12" immersion). The manufacturer further reports that coarse bubble diffusers are typically operated 15 minutes per hour but are used 50 percent of the time during months with higher loadings.[7]

Brookville, Ohio: The VLR system in Brookville, Ohio consists of three tanks in series. The VLR basins are retrofits of 30'W x 60.3'L x 10.7'SWD steel aeration tanks. The aeration basins were converted to VLRs to meet new effluent

TABLE 2.
DESIGN CRITERIA FOR EXISTING VLR SYSTEMS

	Hohenwald	Brookfield	Fries	Brookville	Hillsboro	Hurricane	Ellijay	Willard
Design flow rate, mgd	1.1	1.3	0.22	0.645	0.85	3.0	0.5	4.5
Influent BOD, mg/l		130	240	160	200	200	300	175
Influent NH_3-N, mg/l		15	NA	20	25	30	30	11
Influent P, mg/l		NA	NA	NA	NA	NA	NA	11
Effluent, BOD, mg/l		10	24	10	8		30	10/15*
Effluent NH_3-N, mg/l		1.5/3.0*	NA	1.5/2.5*	2.1		17.4	1.5/5.7*
Effluent P, mg/l		NA	NA	NA	1.0		NA	1.0
BOD removal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Nitrification		Yes	No	Yes	Yes	Yes	Yes	Yes
Phosphorus removal	No	No	No	No	Yes		No	Yes
Temperature, °C		20		20	12	20	20	20
BOD load, lb/1,000 ft^3		13.6	15	16.3	21.9	15	23.1	22
MLSS, mg/l		5,000	4,000	5,000	4,500	5,000	5,000	6,000
HRT at design flow, hrs.		14.2	24	14.7	13.7	20	19.5	11.9
Sludge age, days		25		31.9	17.3	36.5	18.7	17
Total O_2, required, lb/day		3,136		1,462	2,311	12,460	2,264	13,363
Denitrification credit, %		80		80	40	0	0	80
Mechanical alpha		0.95		0.95	0.95	0.95	0.95	0.95
Diffused alpha		0.85		0.85	0.85	0.85	0.85	0.85
DO in Tank #1, mg/l		0		0	0.5	0	2	0
DO in Tank #2, mg/l		1		1	0.5	1	NA	0
DO in Tank #3, mg/l		2		2	2.0	2	NA	1
DO in Tank #4, mg/l					NA	NA	NA	2
Channel velocity, ft/sec		1.2		1.0	1	1.2	1	1
Diffuser clean water OTE, %		17.5		7.5	12	17	18	18
Diffuser submergence, ft.		18.25		9	12	20	20	19
Solids produced, lb/day		1,288	221	520	1,049	2.852	907	6,568

Notes:
1. An asterisk indicates that the values are given as summer requirement/winter requirement.
2. The influent data shown above reflects average values.
3. The effluent data shown above reflects the 30 day average limits.
4. Blank spaces indicate data was not available.

limits which were imposed in July of 1988.[8] Since the conversion to VLR technology (several other process additions and modifications were made simultaneously). The Brookville plant was designed for an average daily flow rate of 0.645 mgd and has treated an average flow of 0.766 mgd over the last 30 months. The effluent BOD, TSS and ammonia nitrogen concentrations have averaged 4.4 mg/l, 7.5 and 0.55 mg/l, respectively.[9] This is compared to an effluent limit of 10.0 mg/l BOD, 12 mg/l TSS and 1.5 mg/l ammonia-nitrogen.

Hillsboro, Ohio: Two existing tanks were retrofit and one new tank was added during the construction of the VLR system in Hillsboro, Ohio. The first basin in the series is 20'W x 127.7'L x 13.5'SWD; the second and third basins are 15'W x 127.7'L x 13.5'SWD. The first basin is operated under anoxic conditions and was designed for biological phosphorus removal. Despite this, alum is currently added to the final clarifier for chemical phosphorus removal.[10] Aeration in this system is provided by two 10 HP disc aerators, two 15 HP disc aerators and coarse bubble diffusers. The Hillsboro plant is designed for an average flow rate of 0.85 mgd and has operated at an average flow rate of 0.894 mgd for the May 1989 to January 1991 time period. The plant has achieved an average effluent CBOD, TSS and ammonia-nitrogen concentration of 4.3, 11.3 and 3.49 mg/l respectively. This is compared to an effluent limit of 10.0 mg/l BOD, 12 mg/l TSS and 1.5 mg/l of ammonia-nitrogen.

Ellijay, Georgia: The VLR system in Ellijay, Georgia is the first installation to include an intrachannel clarifier. This 1.0 mgd system includes two 29'W x 125'L x 20.9' SWD reactors with two 15 HP aerators per reactor. The design criteria given in Table 2 are for one 0.5 mgd reactor but engineers later decided to use two identical 0.5 mgd reactors. The system began operation in January 1991 and operated for approximately two months with limited flows. Full-scale operation has not yet been achieved and no valid operating data is available because the VLR basins were leaking badly due to poor construction.[2]

REFERENCES

1. Miscellaneous information provided by Envirex regarding design criteria, budget costs, etc.

2. Telephone conversations and correspondence with George Smith of Envirex during March, April, May and June of 1991.

3. Telephone conversation and correspondence with Ed Brown of Shaw, Weiss and Denaples on May 24, 1991.

4. Telephone conversation and correspondence with Tracy Mills of Floyd Browne Associates, Inc. on May 24, 1991.

5. Telephone conversation and correspondence with Dewberry & Davis during June of 1991.

6. Performance data for the Hohenwald WWTP provided by the Tennessee Department of Conservation.

7. Operational Report: Fries, Virginia Process Aeration Efficiency Vertical Loop Reactor. November 14, 1990.

8. Brandt, R.A., E.J. Brown, and G.B. Shaw. Innovative Retrofit without Federal Funds: Brookville, Ohio Wastewater Treatment Facilities. Presented at the 63rd Annual Meeting of the Ohio Wastewater Pollution Control Association, June 16, 1989.

9. Performance data for the Brookfield WWTP, the Hillsboro WWTP and the Brookville WWTP provided by the Ohio EPA.

10. Site visit to the Hillsboro, OH wastewater treatment plant on April 26, 1991. The treatment plant operator, Gary Davis, was interviewed during this site visit.

SECTION 3
TECHNOLOGY EVALUATION

PROCESS THEORY

Oxygen Transfer

Aeration in a VLR is typically provided by orbal aeration mixers and a coarse bubble diffuser system. Submersible mixers may, however, be substituted for the discs aerators. To date, the submersible mixers have been used only in the test facility because they provide circulation but no aeration.[1]

In designing a VLR system, as with any wastewater treatment system, the designer must consider both average and peak loadings of both BOD and ammonia when sizing the oxygen supply. For a VLR system, it is common practice to size the aeration discs to provide sufficient oxygen to remove average BOD loadings and to nitrify average ammonia loadings. The coarse bubble diffusers are then sized to provide the additional aeration capacity required for simultaneous peak loadings of BOD and ammonia.

This is a logical approach because the amount of aeration provided by the discs is not easily adjustable. Adjusting the quantity of oxygen provided by the discs generally requires altering the water depth in the reactors, thereby changing the immersion of the discs and their aeration capacity. The manufacturer offers five disc speeds varying from 43 to 55 rpm but does not offer variable speed drives or two speed motors. By contrast, the amount of oxygen provided by the diffusers is adjusted simply by adjusting the output of the blowers (if variable speed blowers or multiple blowers are used) or by operating the blowers intermittently.

In designing aeration systems, the VLR manufacturer typically recommends a mechanical alpha (for the disc aerators) of 0.95 and a diffused air alpha of 0.85.[2] These values represent the high end of the range of values typically used in the industry. They should be used cautiously for normal domestic wastewater. The value of beta used in all available designs is 0.98. This is not unreasonable but will vary with the composition of the wastewater.

Coarse Bubble Diffusers--

In some VLR designs, the coarse bubble diffusers located near the bottom of the reactor are the primary source of oxygen at maximum flow rates. For example,

the Willard VLR system is designed for 262.6 pounds of oxygen per hour supplied by the discs and 294.2 pounds of oxygen per hour supplied by diffused air. By contrast, the Brookfield VLR system is designed for 112.8 pounds of oxygen per hour supplied by the orbal discs and only 23.2 pounds of oxygen supplied by diffused air.[2,3] The Brookfield system was actually operated with no diffused air for approximately seven months. Since that period, diffused air has been used at Brookfield because operating without it caused solids deposition in two of the three reactors.[4]

The VLR manufacturer states that positioning the diffusers below the baffle produces an air bubble residence time which is as much as six times longer than the residence time for a conventional aeration system. The air bubble flow pattern is illustrated in Figure 5.[5] The long residence time allows for more oxygen transfer, producing an oxygen transfer efficiency (OTE) which the VLR manufacturer claims is 1.5 to 2.5 times greater than the OTE for a conventional coarse bubble diffuser system.[6] This would be 25 to 35 percent less than that achievable with state-of-art fine bubble diffusers. The oxygen transfer efficiencies used in various VLR designs is shown in Table 2. Note that the OTE varies with the diffuser submergence in a VLR just as it does in a conventional system.

Results of Walworth County Testing: Clean water oxygen transfer tests were performed at the Walworth County wastewater treatment plant, as mentioned in Section 2. Some of the tests were conducted by an independent testing firm and some were conducted by representatives of the VLR manufacturer. All of the tests performed by the testing firm were completed before the addition of the air release plate. This makes it difficult to evaluate the results, as the manufacturer claims that the addition of the air release plate increased the aeration efficiency. The manufacturer reports that the OTE for the diffusers below the baffle was determined to be 16 percent and that the aeration efficiency of the diffusers was found to be over 4 lbs O_2 per horsepower-hour.[1]

The firm which conducted the Walworth County tests was contacted to confirm the results reported by the VLR manufacturer. A representative of the testing firm quoted the following test results:[7]

Air Flow Rate, SCFM	OTE,%	AE,lb O_2/HP-h
57	16.2	4.3
100	13.6	3.6
150	13.2	3.5
240	12.8	3.4

The above clean water aeration efficiencies (AE) and oxygen transfer efficiencies (OTE) are for the diffusers only. The testing firm stated that the clean water aeration efficiency for the entire aeration system (diffusers and orbal disc aerators) was approximately 3 lb O_2/HP-h.[7]

Aeration Discs--

At low loadings, the coarse bubble diffusers may be operated intermittently to conserve energy. Under these circumstances, the orbal aeration discs, which also circulate the wastewater in a vertical loop, are the primary source of oxygen. As was mentioned in the previous section, some VLR systems are designed so that the majority of the aeration is always provided by the orbal discs. The Brookfield plant is the most extreme example of this. The Brookfield plant is designed so that approximately 17 percent of the oxygen can supplied by the diffusers.[2,3]

<u>Results of Fries, Virginia Testing</u>: Tests were performed at the Fries, Virginia VLR to determine process aeration efficiency. The wastewater flow rate, influent and effluent BOD, temperature and dissolved oxygen (DO) concentration were measured five times a month for ten months. The aeration discs were the primary source of oxygen during these tests because the loadings to the reactor were low during the testing period and the coarse bubble diffusers were not operated constantly.[8]

The Fries test report states that the diffusers were used 25 percent of the time during the majority of the monitoring period (October 1989 to May 1990) and were used 50 percent of the time during September of 1989 and June of 1990.[8] Since the diffusers were used only intermittently during this period, the Fries results primarily reflect the process aeration efficiency of the orbal aeration discs.

From the monitoring results, the VLR manufacturer determined that the process aeration efficiency (PAE) ranged from 1.43 to 4.03 lbs. O_2/HP-h during a ten-month period.[8] The values reported by the manufacturer are summarized in Table 3. The field correction factor (FCF) shown in this table was used to convert the actual oxygen requirements (AOR) to standard oxygen requirements (SOR). The FCF includes adjustments for temperature, elevation, alpha, beta, temperature and dissolved oxygen concentration.

TABLE 3
VLR PROCESS AERATION EFFICIENCIES
(Calculated from Fries Operating Data by the VLR Manufacturer)

Month	BOD in mg/l	Flow mgd	BOD out mg/l	BOD rem lb/day	T°C	DO mg/l	AOR lb/day	FCF	SOR lb/hr	Power eHP	PAE lb/ eHP-h
Sept	112	0.095	6	89	21	5.7	178	0.248	29.9	11.9	2.51
Oct	113	0.082	6	77	17	6.1	154	0.276	23.2	9.2	2.52
Nov	137	0.073	9	83	11	7.1	166	0.302	22.9	9.2	2.49
Dec	169	0.069	9	97	11	7.9	194	0.218	37.1	9.2	4.03
Jan	137	0.065	6	74	11	8.3	148	0.176	35.0	9.2	3.80
Feb	104	0.112	7	97	11	7.0	194	0.312	25.9	9.2	2.82
Mar	115	0.083	3	80	12	6.9	160	0.297	22.4	9.2	2.43
Apr	147	0.085	5	105	13	6.4	210	0.327	25.9	9.2	2.82
May	130	0.095	5	103	17	5.7	206	0.317	27.1	9.2	2.97
June	124	0.064	6	66	19	5.3	132	0.323	17.0	11.9	1.43

1. Definition of terms:
   AOR = Actual Oxygen Requirement
   SOR = Standard Oxygen Requirements (adjusted to standard conditions)
   FCF = Field Correction Factor = AOR/SOR
2. Assumes that ammonia is present at a BOD:NH_3 ratio of 10:1.25.
3. Assumes that complete nitrification occurs.
4. Assumes oxygen requirements of 1.5 lb O_2/lb BOD; 4.6 lb O_2 per lb NH_3.
5. AOR is calculated from the BOD loading, rather than the BOD removed.
6. BOD removed, lbs/day, as reported in Column 5 is actually BOD loading.

The process used by the manufacturer to calculate the actual oxygen requirements during this period must be evaluated. The manufacturer's calculations assumed that 1.5 pounds of oxygen were consumed per pound of BOD loading. It is typical to assume that 1.2 to 1.3 pounds of oxygen will be required for every pound of BOD removed.

The manufacturer further assumed that nitrification occurred and that the influent ammonia concentration was 12.5 percent of the influent BOD concentration. If the sludge age was actually 40 to 50 days during the monitoring period, as the manufacturer claims, then it is likely that nitrification did occur. It is, however, impossible to prove whether nitrification occurred or how much oxygen was consumed during the process since no data is available on influent or effluent ammonia concentrations.

Because of the uncertain nature of the Actual Oxygen Requirements (AOR) values calculated by the manufacturer, the AOR was recalculated by assuming that 1.2 pounds of oxygen were consumed per pound of BOD. All assumptions made by the manufacturer regarding nitrification were retained. These calculations yielded the process aeration efficiencies (PAE) shown in Table 4. A quick comparison between Table 3 and Table 4 shows that the PAE's shown in Table 3 range from 1.43 to 4.03 pounds of oxygen per horsepower-hour, while the corrected PAE's in Table 4 range from 1.23 to 3.45 pounds of oxygen per horsepower-hour.

TABLE 4
VLR PROCESS AERATION EFFICIENCIES
(Not Calculated by the Manufacturer)

Month	BOD in mg/l	Flow mgd	BOD out mg/l	BOD rem lb/d	NH_3 in mg/l	NH_3 out mg/l	NH_3 rem lb/d	T °C	DO mg/l	AOR lb/d	FCF	SOR lb/h	Power eHP	PAE lb/eHP-h
Sept	112	0.095	6	84	14.0	0	11.1	21	5.7	152	0.248	25.5	11.9	2.14
Oct	113	0.082	6	73	14.1	0	9.7	17	6.1	132	0.276	20.0	9.2	2.17
Nov	137	0.073	9	78	17.1	0	10.4	11	7.1	141	0.302	19.5	9.2	2.12
Dec	169	0.069	9	92	21.1	0	12.2	11	7.9	166	0.218	31.8	9.2	3.46
Jan	137	0.065	6	71	17.1	0	9.3	11	8.3	128	0.176	30.3	9.2	3.29
Feb	104	0.112	7	91	13.0	0	12.1	11	7.0	165	0.312	22.0	9.2	2.39
Mar	115	0.083	3	78	14.4	0	10.0	12	6.9	139	0.297	19.5	9.2	2.12
Apr	147	0.085	5	101	18.4	0	13.0	13	6.4	181	0.327	23.0	9.2	2.50
May	130	0.095	5	99	16.3	0	12.9	17	5.7	178	0.317	23.4	9.2	2.54
June	124	0.064	6	63	15.5	0	8.3	19	5.3	114	0.323	14.7	11.9	1.23

1. Definition of terms:
   - AOR = Actual Oxygen Requirement
   - SOR = Standard Oxygen Requirements (adjusted to standard conditions)
   - FCF = Field Correction Factor = AOR/SOR
2. Assumes that ammonia is present at a BOD:NH_3 ratio of 10:1.25.
3. Assumes that complete nitrification occurs.
4. Assumes oxygen requirements of 1.2 lb O_2/lb BOD; 4.6 lb O_2 per lb NH_3.
5. AOR is calculated from the BOD loading, rather than the BOD loading.

Results of Brookfield, OH Testing: Similar tests were conducted at the Brookfield, OH wastewater treatment plant. From the results of these tests, the manufacturer's representatives calculated an average process aeration efficiency of 3.38 lbs. O_2/HP-h.(1) It is difficult to evaluate the manufacturer's calculations for the Brookfield plant's efficiency because insufficient supporting data was provided. It should be noted, however, that the Brookfield PAE calculations assumed an oxygen requirement of 1.4 pounds per pound of BOD removed. It should also be noted that these calculations are based on the period of operation when Brookfield was not using any diffused air.(1,4) Brookfield operators have since decided that diffused air should be used at their facility to avoid solids deposition in the reactors and to maintain an adequate effluent dissolved oxygen concentration.[4,9] It is therefore misleading to use power measurements based on operation without the use of diffused air.

The manufacturer's analysis of the Brookfield data and results states that the process aeration efficiency for a VLR with intermittent diffuser operation is high due to the rapid circulation of the wastewater.[1,8] The disc aeration mixers produce a wastewater circulation rate of 1.0 to 1.5 feet per second. Depending on the dimensions of the basin, the top and bottom zones of the VLR will interchange every one to three minutes. The manufacturer believes that this provides a constant surface renewal of oxygen, resulting in a high PAE.

When designing the disc aeration systems for typical VLRs, the manufacturer recommends a process aeration efficiency of approximately 2.7 lbs. O_2/bHP-hr at field conditions, or 3.4 lb O_2/bHP-hr in clean water.[1] The VLR manufacturer states that the PAE used in current designs is the same as that used for the aerators in their conventional oxidation ditch system, despite the fact that they would expect the PAE in a VLR to be closer to 3.4 lb. O_2/HP-h at field conditions. If the PAE is higher, as expected, the coarse bubble diffusers will be used less than projected by the designs.

The quantity of oxygen provided by the aeration discs is a function of the immersion depth and the shaft speed. The PAE is also affected by the shaft speed. Aeration rates and efficiencies for various immersions and shaft speeds are shown in Table 5. These values were provided by the VLR manufacturer.[1]

TABLE 5
AERATION DISC OPERATIONAL CHARACTERISTICS
FOR 21 INCH DISC SUBMERGENCE

	Base Forward		Apex Forward	
Shaft Speed rpm	Aeration Lb. O_2/hr.	AE Lb. O_2/bHP	Aeration Lb. O_2/hr.	AE Lb. O_2/bHP
43	1.66	3.46	1.25	3.47
46	1.87	3.30	1.40	3.38
49	2.08	3.20	1.55	3.30
52	2.29	3.10	1.70	3.25
55	2.50	3.01	1.85	3.19

Notes:
1. The above values were provided by the VLR manufacturer.
2. bHP = brake horsepower
3. AE = aeration efficiency (clean water)
4. The above values are for a disc immersion of 21".

TABLE 5
AERATION DISC OPERATIONAL CHARACTERISTICS
FOR 21 INCH DISC SUBMERGENCE
(Continued

Notes:
5. The following correction factors are recommended by the manufacturer to adjust for other immersion levels.

DISC SUBMERGENCE (inches)	ADJUSTMENT OF Lb. O_2/hr	DISC SUBMERGENCE (inches)	ADJUSTMENT Lb. O_2/hr
20	0.95	14	0.71
19	0.91	13	0.67
18	0.87	12	0.63
17	0.83	11	0.59
16	0.79	10	0.55
15	0.75	9	0.51

Denitrification Oxygen Credits--

In systems designed for denitrification, the VLR manufacturer claims an oxygen credit for oxygen released during denitrification. This oxygen credit is subtracted from the oxygen requirements and the difference is used to size the oxygen supply. Biological denitrification is considered a fully proven process and it is not within the scope of this work to demonstrate that biological denitrification can occur. The biological concepts involved in denitrification are discussed briefly in this section. Additional details can be found in the literature.[10,11,12]

The denitrification credit is based on 2.86 pounds of oxygen supplied per pound of nitrates as nitrogen denitrified, which is the same value used by others in the industry. The standard oxygen requirement of 4.6 pounds per pound of ammonia as nitrogen nitrified is also used. A typical denitrification credit calculation is as follows:

Assume complete nitrification and 80 percent denitrification. The oxygen credit which can be taken is then developed as follows:

$$\frac{(80\%) * (2.86 \text{ lbs. } O_2/\text{lb. } NO_3\text{-N})}{(4.6 \text{ lbs. } O_2/\text{lb. } NH_3\text{-N})} = 50\%$$

That is, 50 percent of the oxygen required for nitrification will be returned to the biomass by denitrification.

It should be pointed out that the oxygen credit for denitrification in the VLR system is no different than the credit that could be granted for any other suspended growth biological system including oxidation ditches that are designed and operated to achieve either partial or complete single-stage nitrification or denitrification: The VLR manufacturer has chosen to take credit for this in recommending sizing of aeration equipment.

There is sufficient evidence available to prove that denitrification did occur in the Brookfield VLR. In March of 1991, Brookfield began monitoring influent TKN monthly and effluent nitrates and nitrites three times each week. In addition, Brookfield continues to monitor effluent TKN. The data provided by Brookfield is summarized in Table 6.[9]

TABLE 6
BROOKFIELD DENITRIFICATION

Date	Effluent NO_3 and NO_2 mg/l	Influent TKN mg/l	Effluent TKN mg/l
March 4		6.08	1.89
March 18	7.68		
March 19	6.78		
March 20	6.78		
March 25	6.20		
March 26	6.24		
March 27	6.44		
April 1	7.90		
April 2	7.90		
April 3	8.13		
April 9	5.06		
April 10	4.80		
April 15	5.86	22.6	1.37
April 16	5.54		
April 17	5.15		
April 22	4.64		
April 23	4.97		
April 24	4.97		
May		24	1.16
Average	6.18	17.56	1.47
August 1988 to January 1991 (average)			1.55

The percentage of nitrates and nitrites denitrified can be calculated from the data in Table 6 by the following procedure:

1. Assume that the influent concentration of nitrates and nitrites as nitrogen is negligible.[13]

2. Calculate the concentration of nitrates/nitrites formed by decomposition and nitrification of the influent organic and ammonia nitrogen according to the following equation:

$NO_{3f} = TKN_{in} - TKN_{out}$ (neglects assimilated nitrogen)

where

NO_{3f} = concentration of nitrates and nitrites (as nitrogen) formed, mg/l

TKN_{in} = influent TKN concentration, mg/l

TKN_{out} = effluent TKN concentration, mg/l

3. Calculate the percent denitrification by the following equation:

$$\% \text{ denitrification} = (NO_{3f} - NO_{3out})/NO_{3f}$$

If the average values for each parameter are used neglecting nitrogen assimilated by biomass (5 percent of incoming BOD), the results indicate that 62 percent denitrification is occurring. If the measurements taken on April 15 are used, the results indicate that 72 percent denitrification is occurring. The Brookfield VLR was designed for 80 percent denitrification.[2,3] Designers should be aware that closer control of operating parameters are required to assure the 80 percent denitrification oxygen credit and should size aeration equipment accordingly.

Mixing and Circulation

In a standard VLR, the mixing and circulation is provided by aeration mixers. Submersible mixers are available as an alternative; the choice between the two is based on economics. To date, submersible mixers were only used at the VLR test facility. They do not provide any aeration; therefore the power is used more efficiently by the discs, which both mix and aerate. Information from the Brookfield VLR indicates that the diffused air equipment contributes mixing energy as well.[4,9]

Circulation around the horizontal baffle is normally designed for an average rate of 1.0 to 1.5 feet per second.[6] Two of the VLR systems described in Table 2 are designed for a velocity of 1.2 feet per second; four of the systems are designed for 1.0 feet per second.

The design engineer for the Brookville VLR performed velocity tests but did not document the results. The only information available from these tests was that there was a wide variation in the velocity vertically throughout the tank.[14] Because the discs are positioned near the surface, the water velocity is believed to be highest near the surface of the water and near the bottom of the VLR.

The contract specifications for the Brookfield VLR required a velocity of 1.0 to 1.5 feet per second in the reactors. Performance tests were conducted to determine the velocity but the results were found to be unreliable due to the turbulence in the basin. The velocity test was then replaced by a mixed liquor suspended solids profile test. The initial MLSS profile showed solids deposition in the smaller two of the three basins. The disc speed was increased and the diffused air system began (or resumed) operation. After these changes were made, the mixing equipment passed the MLSS profile test.[4] It is suggested that both average velocity and mixing criteria be included in VLR specifications.

The operator of the Hohenwald WWTP noted that the configuration of the diffusers in the VLRs has a significant effect on the circulation. A further discussion on diffuser configuration can be found in this section. The operator changed the diffuser configuration and checked the surface velocity by timing the movement of a piece of styrofoam. He found that the new diffuser configuration increased the velocity by one foot per second over the previous configuration.[15]

Biological Concepts

Denitrification--

Biological nitrification and BOD removal require oxygen. Biological denitrification is sometimes incorrectly referred to as a anaerobic process. In actuality, denitrification is accomplished by facultative bacteria which utilize nitrates (NO_3) and nitrites (NO_2) in place of oxygen under anoxic conditions.[11] This process consumes carbonaceous materials without removing free oxygen from the system, thus reducing the total oxygen requirement of the total system.

Denitrification is a two-stage process. In the first stage, nitrates and carbonaceous materials are consumed, producing nitrites and water. In the second step, nitrites and carbonaceous materials are consumed, producing nitrogen gas (N_2), carbon dioxide (CO_2), water and hydroxide ions (OH^-). The hydroxide ions contribute to the alkalinity of the wastewater, replacing a portion of the alkalinity which was removed during nitrification[11].

The manufacturer states that the stratified oxygen profile frequently used in VLRs configured in series allows BOD removal, nitrification and denitrification to occur in the same basin.[2] When a VLR system is designed for BOD removal, nitrification and denitrification, a dissolved oxygen (DO) concentration close to zero is maintained in the first basin. A higher DO concentration will be maintained in the remaining basins--the DO concentration in the last basin should be above 2.0 mg/l. Some VLR designs have reported D.O. levels of 2 to 9 mg/l, which is much higher than the process needs.

Mixed liquor from the last basin is transferred to the final clarifier. The return activated sludge from the final clarifier is recycled to the first basin or wasted. This sludge has a high DO concentration, although the mixed liquor in the first basin has a low DO. The manufacturer claims that this combination provides sufficient oxygen for nitrification and BOD removal to occur in certain zones in the first basin, while other zones in the same basin are anoxic and are denitrifying.[2]

Phosphorus Removal--

Biological phosphorus removal has been documented in various types of activated sludge treatment plants where the wastewater is subjected to both anaerobic and aerobic conditions. When an anaerobic stage is placed at the beginning of the activated sludge system, it will exert a particularly positive effect on the development of phosphorus-storing microorganisms. The high BOD concentration of the wastewater entering the anaerobic stage causes fermentation, which produces acetate and other fermentation products. The phosphorus-storing microorganisms are able to assimilate the fermentation products in this anaerobic environment. Because many competing microorganisms cannot function in this manner, this type of operation gives the phosphorus-storing microorganisms a distinct advantage.[16,17]

During the aerobic phase, the phosphorus-storing microorganisms will take up more phosphorus than they actually require to function and store the phosphorus as polyphosphates. This "luxury uptake" of phosphorus is maximized at dissolved oxygen concentrations of 2.0 mg/l or higher. If the microorganisms are subjected to an environment with a low DO concentration, the excess phosphorus will be released. It is therefore essential to biological phosphorus removal that the sludge be wasted under aerobic conditions to ensure that the phosphorus is not released from the sludge back into the wastewater. For similar reasons, an aerobic environment should be maintained in the final clarifiers and for the return activated sludge.

The above process theory is utilized in VLRs designed for biological phosphorus removal. At Hillsboro, for example, the design dissolved oxygen concentrations are 0.5 mg/l, 0.5 mg/l and 2 mg/l in the first, second and third basins, respectively.[1] The Willard VLR system is also designed for biological phosphorus removal. Design DO concentrations are 0 mg/l, 0 mg/l, 1 mg/l and 2 mg/l in the first, second, third and fourth reactors, respectively.[2,3]

The VLRs at the Hillsboro WWTP are not achieving adequate biological phosphorus removal. Supplementary alum is added in the final clarifier but data received from the Ohio EPA indicates that the effluent phosphorus concentration still exceeds the effluent limit of 1.0 mg/l over half of the time.[18] It is unclear whether the apparent problems with biological phosphorus removal at Hillsboro are due to the VLR design or the lack of operator training.[19]

The operators at the Hillsboro did not receive significant training from either the design engineer or the VLR manufacturer. Representatives of both companies stated that training was not provided because it was not specified by the contract.[2,20] As a result, at the time of the site visit the Hillsboro VLR was apparently being operated with DO concentrations appropriate for phosphorus removal but the operational theory had never been explained to the operators.[19]

The Brookfield WWTP is required to monitor effluent concentrations of phosphorus despite the fact that the plant's NPDES permit does not specify an effluent phosphorus concentration. The phosphorus concentration is measured monthly and performance data is provided in Chapter 4. The average effluent phosphorus concentration for the reporting period was 2.2 mg/l.[18] Typical untreated weak domestic wastewater contains 4 mg/l of phosphorus,[13] but the Brookfield wastewater is extremely weak (the average influent BOD concentration during the reporting period was 85 mg/l). Since the influent concentration is not monitored, it is not possible to determine whether significant biological phosphorus removal is occurring. No significant operating data is currently available from the Willard VLR system.

Stormwater Bypass

The manufacturer claims that VLR systems which are configured in series and include a stormwater bypass are capable of handling storm flows up to five times the average design flow without significant solids washout (Storm-flow as used herein is defined as high Infiltration/Inflow in separate sanitary sewers). If the treatment facility is experiencing excess flows or expects high flows in the near future, the storm flow bypass can be used to ensure treatment while minimizing solids washout.

A typical storm flow configuration is shown in Figure 6. During high flows, the influent is channeled into the third reactor, bypassing the first two tanks. The effluent from the VLR flows to the final clarifier and the return activated sludge from the clarifier is pumped into the first reactor in the series. The effluent quality is lower than average but the MLSS concentration in the first and second reactors is preserved and solids washout is prevented. This ensures that the system effluent will return to normal almost immediately when the flow rates decrease and the bypass is discontinued. Section 4 describes the performance of the Brookfield VLR in the stormwater bypass mode during a period of excess flows.

Conventional activated sludge systems may experience excess solids carry over from the secondary clarifiers due to high clarifier overflow rates and the fact that all of the MLSS is subject to hydraulic wash-through to the secondary clarifier. This can be mitigated somewhat by higher return solids pumping but does not offer the advantage of MLSS basin isolation. The stormwater by-pass feature described herein is not unique to the VLR, but may also be incorporated into conventional plug flow aeration basins.

Design Criteria

Design criteria for a typical domestic waste with an influent BOD concentration of 220 mg/l are shown in Table 7. In addition, designs for plants currently in operation or under construction can be found in Table 2. A representative of the VLR manufacturer stated that their recommended design criteria becomes increasingly conservative as the flow rates decrease. A larger safety factor is recommended for the design of small systems to account for the increased probability and severity of shock loadings.[2,3,14,21]

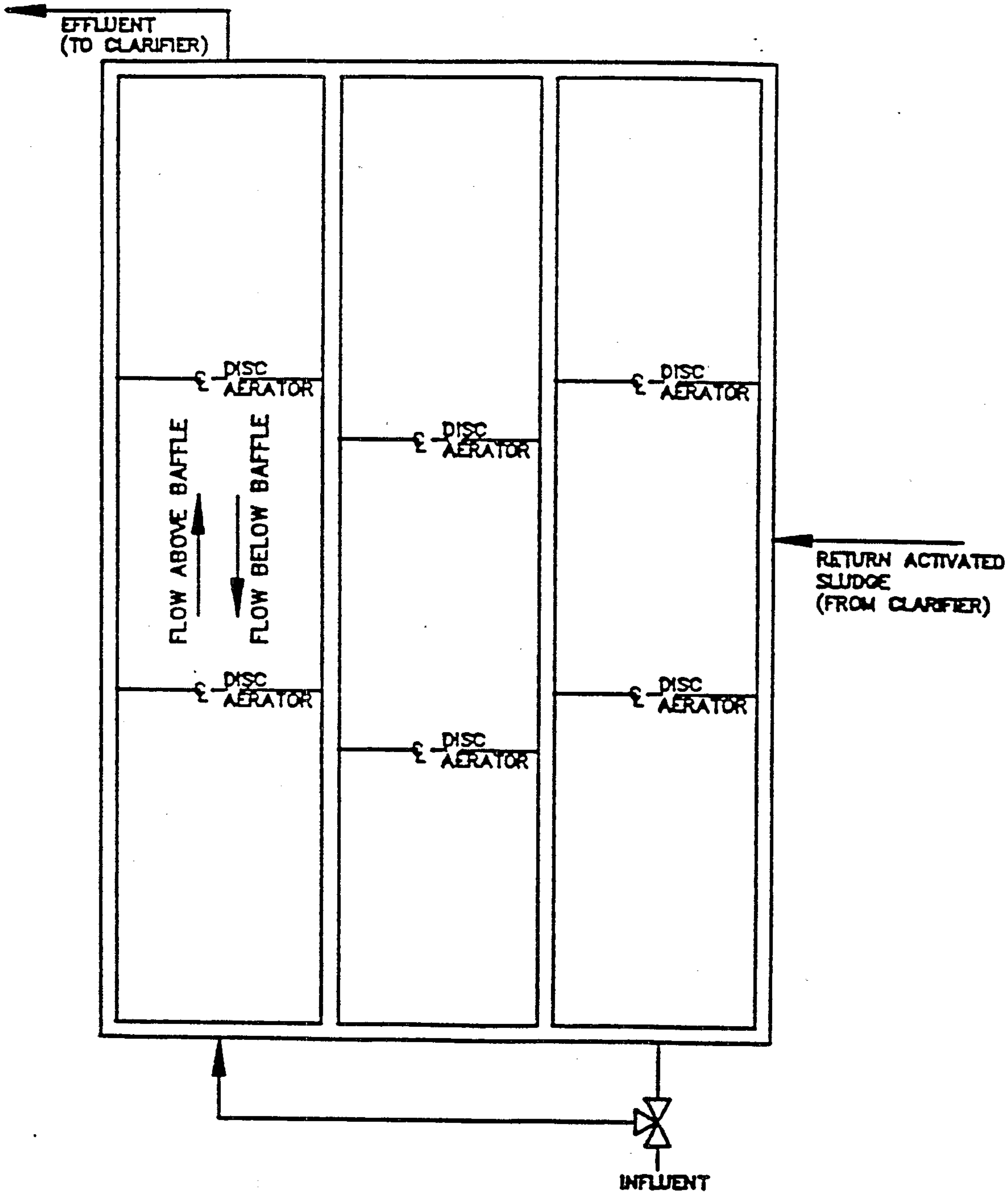

Figure 6
Storm Flow Bypass Configuration for Vertical Loop Reactors in Series

TABLE 7
VERTICAL LOOP REACTOR DESIGN CRITERIA[1]

Design size, mgd:	1.0	2.0	5.0 or more
BOD loading, lbs/1,000 ft3	19	27	34
MLSS, mg/l	4,000	4,500	5,000
HRT, hours	17	12	10
SRT, days	28	23	20
Lb. solids produced/lb. BOD	0.82	0.82	0.82
Sludge age, days			11.2
Aerobic digestion, days			20
Lb. O_2 required/lb. BOD[2]			1.15
Lb. O_2 required/lb. ammonia			4.6
Denitrification credit, %			80
Alpha mechanical			0.95
Alpha diffused			0.85
Beta			0.98
DO in tank #1, mg/l			0.0
DO in tank #2, mg/l			1.0
DO in tank #3, mg/l			2.0
Channel velocity, ft/sec			1.0
Power use per disc, bHP			0.32
Lb. O_2 per disc			1.1
Diffuser clean water OTE, %			18
Diffuser submergence, ft.			19
Blower efficiency			0.7
Clarifier loading, gpd/ft2			353

1 These design criteria are based on a temperature of 20°C, an influent BOD concentration of 220 mg/l, 25 mg/l of ammonia to be nitrified, an effluent BOD concentration of 5 to 10 mg/l, an effluent suspended solids concentration of 5 to 10 mg/l and an effluent ammonia concentration of 0.0 to 0.5 mg/l.

2 Note that this value is significantly lower than that used by the VLR manufacturer to determine aeration efficiency as shown on Table 3.

Hydraulic Design--

If the stormwater bypass feature is to be included in a VLR design, the influent or effluent structure must include the necessary bypass gates, valves or weirs to allow for bypass operation. Depending on the bypass configuration used, the VLR influent may be channeled to a reactor which is at the end of the reactor series during normal operation. The other option is to channel the VLR

effluent such that it flows out of the first or second reactor, bypassing all subsequent reactors.

The bypass design must also include gates between the reactors such that one or more of the reactors in a series can be isolated. Wastewater should not flow to or from the isolated reactors, although the return activated sludge must be pumped to one of the isolated reactors. Ideally, all bypass equipment will be electronically actuated so that the stormwater bypass can be easily and quickly activated or deactivated.

In certain cases, it will be advantageous to include an effluent weir in the reactor design. An effluent weir gate will make it possible to adjust the water level in the VLRs, thereby adjusting the aeration disc immersion. This will generally be the only practical way to adjust the disc immersion, which is necessary if it is desired to adjust the amount of aeration provided by the disc aerators. The first two VLRs installed did not have level control but the following three (Brookville, Fries and Hillsboro) all have some degree of level control.

Disc Aerator Placement--

When multiple VLRs are designed with common walls, it is prudent to stagger the location of the disc aerators. That is, the drive for a disc aerator in the first basin should not be directly across from the drive for an aerator in the second basin. Experience has shown that this type of configuration makes it more difficult to access the drives for maintenance purposes.[19] A specific situation where the drives for three basins are in the same line is mentioned further on in this section.

Diffuser Configuration--

The Hohenwald WWTP operator noted that the configuration of the diffusers in a VLR has a significant effect on the circulation. When the Hohenwald VLR was originally constructed, the diffusers were perpendicular to the flow in the reactor. The operator suspected that this was impeding the circulation, so he rearranged the diffused air system in one basin such that the diffusers were parallel to the flow. He found that this diffuser configuration increased the velocity by one foot per second over the original configuration. He has since reconfigured a second basin and plans to change the third basin when he has the opportunity.(15) A representative of the VLR manufacturer stated that VLR systems are currently designed with the diffusers parallel to the flow.[2]

Process Design

The VLR manufacturer will provide assistance to individuals who are involved in designing a new or renovated wastewater treatment system which includes a VLR. In addition, the manufacturer will provide a process warranty for their designs. The performance guarantee provided for the Willard WWTP is discussed in this section.

In the design of a VLR system, the oxygen requirements recommended by the manufacturer may be of particular concern. In past designs, some engineers have decided to follow the oxygen requirements recommended by the manufacturer and have subtracted the denitrification credit from the amount of oxygen required for BOD removal and nitrification. Other engineers have chosen a more conservative approach when determining total oxygen requirements. This is a choice which must be made by the individual designer.

Reactor Configurations

VLRs may be configured in parallel or in series. Flow patterns and configurations for VLRs in parallel and in series are shown in Figures 2 and 3, respectively.

Vertical Loop Reactors in Series--

Five of the seven operating VLR systems are configured in series. VLRs in series can be operated with stratified dissolved oxygen (DO) profiles, which provides several advantages. Stratified DO profiles are particularly useful in systems designed for denitrification and/or phosphorus removal. Details on the application of stratified DO profiles to denitrification and phosphorus removal are found in this section.

Vertical Loop Reactors in Parallel--

The VLR system in Fries, Virginia includes two reactors which are designed for parallel operation, although only one is currently in use. Parallel reactors have several advantages over individual reactors. These include reduced material costs (they share a common wall) and increased process flexibility. Parallel reactors are convenient for treatment facilities which currently have low loadings but project significant increases in the future.

For a typical plant, however, it will generally be advantageous to operate multiple VLRs in series rather than in parallel. The Hohenwald VLR system can be operated in series or in parallel. The Hohenwald VLRs are currently operated in series because this produces a better effluent than does parallel operation.[15]

Weather Protection Equipment

Optional equipment is available to protect the VLR components in cold weather. Hoods may be installed to cover the aeration discs and prevent snow and rain freezing on the discs. Ice guards may be installed upstream of each aerator to keep large pieces of ice away from the discs. Splash guards are available for the ends of the aerator shafts. These may be used to avoid splashing wastewater onto the bearings.[1]

COMMON MODIFICATION OF VERTICAL LOOP REACTOR DESIGNS

Intrachannel Clarifier

The VLR system in Ellijay, Georgia includes an intrachannel clarifier, thereby eliminating the need for a separate clarifier. The intrachannel clarifier also eliminates the return activated sludge (RAS) pumping required in a standard configuration.[1] It is not possible to evaluate the performance of the intrachannel clarifier when installed in the VLR process at this time, as no significant operating data is available.

O&M COMPLEXITY AND REQUIREMENTS

Routine Maintenance

The operators of all municipal wastewater treatment plants which have employed VLRs for over six months were interviewed during the preparation of this report. Site visits were made to Brookville, Hillsboro and Brookfield; the operators of the Fries and Hohenwald wastewater treatment plants were interviewed on the telephone. All operators stated that the VLR did not require much maintenance. The operators' estimates of the VLR maintenance time ranged from two hours per week to two hours per day and did not seem to be related to the design flow rate. The maintenance tasks listed by the operators included adding oil, changing the oil, lubricating bearings and cleaning.[9,15,19,22,23]

Operators who had previously worked with other types of biological treatment systems were asked to compare the maintenance requirements of those systems to a VLR. The Hillsboro operator stated that the maintenance requirements for a VLR were about the same as for a two-stage activated sludge system.[19] The Hohenwald operator said that the VLR maintenance did not require much more time than the trickling filter he had worked with previously.[15] A third operator stated that the Brookville VLR requires only about half as much maintenance as the activated sludge system it replaced.[22]

Definitive comparisons between the maintenance requirements of VLRs versus. competing technologies cannot be made based on the limited data available. It would seem reasonable however to expect a slightly higher maintenance cost for VLRs than for oxidation ditches became of the dual aeration system, limited access to diffusers, and the mechanical components associated with the adjustable effluent weir.

Major Maintenance

During the preparation of this report, a site visit was made to the Brookville WWTP. The Brookville VLR has been in operation for over two and a half years. During this period, it has not been necessary to repair or replace any portion of the VLR.[22]

The second site visit was to the Hillsboro VLR, which has been in operation for approximately two years. At the time of the visit, the plant employees were preparing to replace a bearing in a disc aerator drive shaft. To the best of their knowledge, this was the first repair on the VLR since start-up (the plant has three basins and six disc aerators). The bearing was under warranty, so a new bearing was supplied by the manufacturer at no cost to the plant.[19]

The Hillsboro operator was disappointed, however, that the manufacturer was not willing to make the repair. Replacing a bearing in the Hillsboro VLR system is particularly difficult because the disc aerator drives in the three tanks interfere with each other. This makes it necessary to raise the drive shaft much higher than would be required in a different system. For this reason, the operator plans to have false work installed in the basin to support a jack to lift the drive shaft. The design issues associated with this problem were discussed previously in this section.

The Hillsboro operator also mentioned a problem which occurred at start-up. The turning vanes on the Hillsboro VLR collapsed when the water began circulating through the basins. They were repaired and strengthened and have not presented any further problems.[19]

The third site visit was made at the Brookfield WWTP, where a VLR system has been in operation since November of 1987. The only major VLR maintenance which has been required was the replacement of a bearing on one of the four disc aerator drives. The operator believes that the problem was caused by faulty installation, since the bearing failed out almost immediately after start-up and no other bearings have required replacement.[9]

Both of the operators who participated in telephone interviews have experienced problems with their disc aerator drives. The Hohenwald operator stated that he has replaced six aerator drives in less than four years of operation. The Hohenwald WWTP has four disc aerators, indicating an average drive life of about two and a half years. When this problem was discussed with the manufacturer, a representative stated that the Hohenwald plant has had to replace a number of drives because the wrong type of lubricant was being used.[2,15]

The operator of the Fries treatment plant stated that the only major maintenance required on the Fries VLR involved the gearbox which drives the disc aerators. It has been necessary to replace bearings in each of the two aerators in this VLR system.[23] These VLRs have been in operation for over three years, but only one aerator is used at a time. Based on this information, each of the aerator drives at the Fries WWTP has required one or more new bearings after less than one and a half years of operating time.

<u>Operation</u>

When operators were questioned about the time required to operate a VLR system, their responses varied from one to three hours per day. Operating tasks included monitoring dissolved oxygen concentrations, pH, sampling, sample analysis and reporting.[9,15,19,22,23] The variation in operating times seemed to be primarily dependent on the amount of sample analysis done in-house. Design flow rates did not have a significant effect on operating time.

The Hillsboro operator stated that the operational complexity and time requirements of a VLR were similar to those for a two-stage activated sludge system. The only operational difference he mentioned was that he found it easier to handle upsets in a two-stage activated sludge system than in a VLR.[19] A second operator stated that it is more difficult to operate a VLR than a trickling filter because the VLR requires more testing. He also mentioned, however, that the VLR seems to handle upsets better than a trickling filter.[15] The Brookville operator commented that it was possible to operate the VLR system under a wide range of MLSS concentrations and still meet the effluent requirements.[22]

Table 8 summarizes the use of unique design features of the VLR by five of the seven plants evaluated. Interviews with operators of the VLR systems indicated that in general, the operators were unfamiliar with the overall capability and flexibility of the VLR system to achieve varying levels of nutrient control. Adequate site specific, process oriented training was notprovided by either the manufacturer or the design engineer for any of the VLR systems evaluated.

TABLE 8
USE OF CLAIMED VLR ADVANTAGES

Facility	Denitrification	Stormwater Bypass	Effluent Weir	Biological P Removal
Hohenwald, TN	Unknown	Yes	No	No
Brookfield, OH	Yes	Yes	No	No
Fries, VA	No	No	Yes	No
Brookville, OH	Unknown	No	Yes	No
Hillsboro, OH	Unknown	No	No	No

PERFORMANCE GUARANTEE

The manufacturer will provide a performance guarantee for VLR installations. The parameters specified include the effluent concentrations of $CBOD_5$, suspended solids, NH_3-N and phosphorus.[24]

In addition to the above process guarantee, the manufacturer provides a mixing guarantee that states that the mixing equipment must maintain a "MLSS concentration within 10 percent of the high and low readings in each tank." If the disc aerators do not meet the mixing guarantee, the manufacturer "shall, at no cost to the owner, provide and install velocity deflector baffles, and demonstrate the desired velocities and mixing."[24]

The performance guarantee is based on the following conditions:

1. The VLR must be installed and built in "strict compliance" with the manufacturer's specifications.

2. The VLR system must be installed and built in "strict compliance" with the specifications of the design engineer.

3. The owner shall provide operational conditions and influent wastewater which meet certain criteria.

The performance guarantee describes the circumstances of a 60 day "Performance Test" in detail. Before the Performance Test will be conducted, the entire treatment plant must be operational and the VLR must operate within a specified set of operating conditions for a minimum of thirty consecutive days. However, the Performance Test must also be conducted within a certain time frame. If the owner does not begin testing within this time period, the "system shall be deemed accepted."[24] The "Performance Test" specified by the manufacturer is highly qualified and contains terms and conditions that severely limits the manufacturer's liability in the event of a legitimate process failure.

The performance guarantee does not appear to directly address the issue of oxygen supply. That is, the guarantee provided to Willard, OH does not guarantee that the system will be able to achieve the design DO concentrations. Rather, the oxygen content in the reactors is one of the operational conditions which the owner must supply for the performance guarantee to be valid. However, the performance specifications do state that if "the results of the test indicate a deficiency in the system to meet the performance or design guarantees" the manufacturer will "take additional data, perform design and engineering work, make adjustments to the system, check and revise the owner's operating procedures and then request a new performance test."

REFERENCES

1. Miscellaneous information provided by Envirex regarding design criteria, budget costs, etc.

2. Telephone conversations and correspondence with George Smith of Envirex during March, April, May and June of 1991.

3. Telephone conversation and correspondence with Tracy Mills of Floyd Browne Associates, Inc. on May 24, 1991.

4. Floyd Browne Associates, Inc. Performance Certification Report. Submitted to Trumbull County on April 29, 1989.

5. Brandt, R.A., E.J. Brown, and G.B. Shaw. Innovative Retrofit without Federal Funds: Brookville, Ohio Wastewater Treatment Facilities. Presented at the 63rd Annual Meeting of the Ohio Wastewater Pollution Control Association, June 16, 1989.

6. Huibrestse, G.L., G.W. Smith, D.J. Thiel, and J.W. Wittmann. Introduction to the Vertical Loop Reactor Process. June 12, 1986.

7. Telephone conversations with Greg Hubert of Radian on April 30, 1991 and May 2, 1991.

8. Operational Report: Fries, Virginia Process Aeration Efficiency Vertical Loop Reactor. November 14, 1990.

9. Site visit to the Brookfield, OH wastewater treatment plant on May 15, 1991. The treatment plant operator, Daniel Earhart, was interviewed during this site visit.

10. Johnson, W.K. and Schroepfer, G.J. Nitrogen Removal by Nitrification and Denitrification. Journal WPCF, August 1964.

11. Process Design Manual for Nitrogen Control. U.S. Environmental Protection Agency. October, 1975.

12. Schroeder, E.D. and Busch, A.W. The Role of Nitrate Nitrogen in Bio-Oxidation. Journal WPCF, November 1968.

13. Metcalf & Eddy, Inc. Wastewater Engineering: Treatment, Disposal, Reuse. McGraw-Hill, 1979.

14. Telephone conversation and correspondence with Ed Brown of Shaw, Weiss, and Denaples on May 24, 1991.

15. Telephone interview of Paul Webb on April 18, 1991. Mr. Webb is the Hohenwald, TN wastewater treatment plant operator.

16. Design Manual for Phosphorus Removal. EPA/625/1-87/001, U.S. Environmental Protection Agency, Center for Environmental Research Information and Water Engineering Research Laboratory, Cincinnati, OH, September, 1987.

17. Goronszy, M.C. Simplified Biological Phosphorus Removal in a Fed-Batch Reactor Without Anoxic Mixing Sequences.

18. Performance data for the Brookfield WWTP, the Hillsboro WWTP and the Brookville WWTP provided by the Ohio EPA.

19. Site visit to the Hillsboro, OH wastewater treatment plant on April 26, 1991. The treatment plant operator, Gary Davis, was interviewed during this site visit.

20. Telephone conversations with Woolpert engineers during May of 1991.

21. Telephone conversation and correspondence with Dewberry and Davis during June 1991.

22. Site visit to the Brookville, OH wastewater treatment plant on April 19, 1991. During this visit, Ron Brandt and Jon Weist were interviewed. Mr. Brandt is the Brookville WWTP operator; Mr. Weist is his assistant.

23. Telephone interview of Eugene Graham on April 18, 1991. Mr. Graham is the Fries, VA wastewater treatment plant operator.

24. Willard, OH wastewater treatment plant performance specifications.

SECTION 4

PERFORMANCE

PERFORMANCE SUMMARY

Performance data for the five VLRs which have over six months of valid operating data is summarized in Tables 9 through 13. This data was obtained from the state and local agencies in Ohio, Tennessee and Virginia.[1,2,3]

As shown in Table 9, the Hohenwald plant is operating below the design flow rate of 1.1 mgd but is meeting effluent requirements easily. Hohenwald has exceeded its 30-day ammonia permit limit only once (excluding the first three months of operation) and has never exceeded its 30-day BOD_5 permit limit (excluding the first two months of operation).[3] Similarly, the Fries VLR is operating below the design flow rate of 0.22 mgd and has never, excluding the first month of operation, exceeded the effluent 30-day BOD_5 limit.[2]

As shown in Table 10, the Brookfield system is operating above the design flow rate of 1.3 mgd and is consistently achieving effluent concentrations well below the required levels.[1] Brookville is also operating well. The plant effluent has only exceeded the 30-day TSS limit twice and the 30-day ammonia limit once in thirty months of operation. The 30-day BOD_5 limit has never been exceeded.[1]

The Hillsboro VLR, Table 13, which has an average flow rate slightly higher than the design capacity of 0.85 mgd, has experienced numerous violations of 30-day effluent limits for ammonia, TSS and phosphorus. The 30-day BOD limit has also been exceeded twice.[1] The effluent BOD appears to be related to the flow rate. The two months with excessive effluent BOD's were also the two months with the highest influent flow rates.

Performance During Periods of Excess Flows

Performance data was collected at the Brookfield VLR, during a period of excess flows. This plant was constructed with the stormwater bypass feature discussed in Section 3. The design flow rate is 1.3 mgd; a flow of 4.8 million gallons was recorded for a 24-hour period during this event. The VLR bypass configuration described in Section 3. was used with excellent results. The data collected during this period of excess flows was obtained from the VLR manufacturer and is presented in Table 14.[4] The Brookfield VLR performanceduring this period of excess flows may be compared to the overall performance data for the Brookfield facility, which is shown in Table 10.

APPLICATIONS AND LIMITATIONS

Applications

As shown in Tables 9 through 13, VLRs are capable of producing a very high quality effluent ($CBOD_5$ less than 10 mg/l; TSS less than 10 mg/l; NH_3-N less than 1.0 mg/l). The VLR technology may be appropriate for wastewater treatment plants which have stringent ammonia or BOD limits. The process is also applicable for moderate degrees (60 to 80 percent) of total nitrogen and phosphorus removal.

VLRs are applicable over a wide range of flow rates and influent BOD loadings. The multiple basin series arrangement with the stormwater bypass is applicable for facilities with high peak to average flow ratios.

A VLR facility should be considered when land area is an important concern. A VLR requires significantly less area than an oxidation ditch or a conventional activated sludge treatment plant. Land area requirements are discussed further in Section 5.

VLRs should also be considered when it is possible to retrofit existing basins to meet increased flow or more stringent effluent requirements. Two of the VLR systems currently in operation were constructed as retrofits of existing aeration basins. The effluent from the aeration basins which were used at the Brookville WWTP prior to 1988 did not meet the requirements of the NPDES permit issued to Brookville effective July 1, 1988. The summer ammonia limit of 1.5 mg/l was of particular concern. The retrofit, which did not require the construction of any additional aeration basins, has allowed Brookville to comply with this ammonia limit.[5]

The Hillsboro VLR system includes two retrofit reactors and one new basin. The Hillsboro operator stated that the previous activated sludge system was designed for approximately 0.5 mgd, while the current VLR system is designed for 0.85 mgd.[6]

Limitations

Because there is a limited amount of operating information available on VLRs, the operators may feel that they cannot get assistance with operational problems. There appears to be a lack of understanding on the part of both designers and operators concerning the applicability and flexibility of the process for nutrient control.

TABLE 9.
HOHENWALD EFFLUENT MONITORING DATA
(Monthly Averages from Operating Reports)

Month/Year	Flow mgd	Temp °C	BOD_5 mg/l	TSS mg/l	NH_3-N mg/l	MLSS mg/l	VLR DO mg/l
Jul 1987	0.489		37.0	37.0	11.10		
Aug 1987	0.594		52.0	9.0	14.00		
Sep 1987	0.339		5.0	5.0	3.00		
Oct 1987	0.347		4.0	4.0	0.50		
Nov 1987	0.313		5.0	8.0	0.54		
Dec 1987	0.624		6.0	11.0	0.26		
Jan 1988	0.761	10.0	5.0	10.0	0.40	3263	4.9
Feb 1988	0.875	10.6	4.0	8.0	0.12	3508	5.9
Mar 1988	0.674	13.3	4.2	8.0	0.13	3916	2.5
Apr 1988	0.610	16.5	4.0	7.0	0.15	5155	2.9
May 1988	0.346	19.0	4.0	7.0	0.37	5766	2.3
Jun 1988	0.218	21.8	4.0	6.0	0.33	6637	2.3
Jul 1988	0.270	23.0	4.0	7.0	0.36	5948	2.9
Aug 1988	0.286	23.8	4.0	5.0	0.25	3526	3.7
Sep 1988	0.326	22.8	3.0	4.0	0.50	3794	3.7
Oct 1988	0.232	20.7	4.0	3.0	0.18	3256	4.1
Nov 1988	0.450	17.9	4.0	4.0	0.22	2417	4.6
Dec 1988	0.603	14.8	5.0	7.0	0.30	2135	5.1
Jan 1989	0.860	13.6	5.0	5.0	0.11	2549	5.5
Feb 1989	0.872	12.9	5.0	4.0	0.12	3556	4.4
Mar 1989	0.628	14.0	3.0	3.0	0.11	3606	3.0
Apr 1989	0.532	16.4	3.0	2.0	0.18	3168	3.1
May 1989	0.536	19.0	3.0	4.0	0.40	4814	1.5
Jun 1989	0.520	21.0	1.8	4.5	0.20	3688	1.6
Jul 1989	0.811	22.3	2.0	3.0	0.40	5266	3.0
Aug 1989	0.351	23.4	2.5	3.0	0.20	4290	1.2
Sep 1989	0.483	22.7	2.0	3.0	0.20	4390	3.6
Oct 1989	0.514	20.9	1.8	1.9	0.10	4224	4.9
Nov 1989	0.561	17.9	2.0	2.1	0.10	3893	5.0
Dec 1989	0.225	13.5	2.5	3.0	0.17	3589	5.8

TABLE 9
HOHENWALD EFFLUENT MONITORING DATA
(Monthly Averages from Operating Reports)
(Continued)

Month/Year		Flow mgd	Temp °C	BOD_5 mg/l	TSS mg/l	NH_3-N mg/l	MLSS mg/l	VLR DO mg/l
Jan 1990		0.704	12.9	2.3	3.0	0.20	3023	5.7
Feb 1990		0.639	14.3	2.4	3.0	0.14	3260	5.6
Mar 1990		0.596	14.9	2.3	3.7	0.15	3467	4.1
Apr 1990		0.389	16.2	2.0	4.0	0.13	4150	3.4
May 1990		0.655	18.3	2.4	3.0	0.20	4418	2.4
Jun 1990		0.368	20.5	3.0	4.0	0.40	6405	1.8
Jul 1990		0.387	22.0	3.0	4.0	0.30	4409	2.8
Aug 1990		0.238	23.0	3.0	4.0	0.20	3835	2.0
Sep 1990		0.236	23.0	2.0	3.0	0.20	3636	1.4
Oct 1990		0.186	21.0	2.0	2.0	0.20	3322	1.7
Nov 1990		0.300	18.0	3.0	5.0	0.40	3314	3.5
Dec 1990		0.752	15.0	3.0	4.0	0.13	2300	5.9
Jan 1991		0.529	13.0	4.0	4.0	0.80	2787	4.2
Feb 1991		0.747	12.9	4.0	5.0	0.90	3076	4.3
Mar 1991		0.613	14.0	4.0	4.9	1.30	2844	3.6
Apr 1991		0.789	17.0	2.3	3.3	0.50	3997	1.5
Summary:	Minimum	0.186	10.0	1.8	1.9	0.10	2135	1.2
	Maximum	0.875	23.8	52.0	37.0	14.00	6637	5.9
	Average	0.508	17.7	5.1	5.4	0.89	3865	3.5
	Limit	NA	NA	25.0	45.0	1.00	NA	NA

Notes:
1. The Hohenwald VLR began operation in July 1987.
2. Blank cells indicate data which was not available.

TABLE 10.
BROOKFIELD EFFLUENT MONITORING DATA
(Monthly Averages from Operating Reports)

Month/Year		Flow mgd	Temp °C	TSS mg/l	NH_3-N mg/l	TKN mg/l	P mg/l	BOD_5 mg/l
Aug 1988		1.128	22.3	1.4	0.15	2.19	3.78	1.7
Sep 1988		1.176	20.2	1.8	0.07	2.66	4.00	1.8
Oct 1988		1.144	16.9	2.0	0.21	1.79	3.60	1.6
Nov 1988		1.794	13.0	2.3	0.13	1.43	2.20	1.7
Dec 1988		1.433	9.8	1.8	0.16	1.60	1.00	1.5
Jan 1989		1.732	8.7	1.6	0.14	1.11	2.20	1.6
Feb 1989		1.736	7.6	2.7	0.15	1.15	1.40	1.6
Mar 1989		1.748	8.8	5.7	0.30	1.19	1.80	2.2
Apr 1989		1.891	10.2	2.5	0.30	1.36	1.20	1.7
May 1989		1.976	12.8	3.1	0.12	1.45	1.70	1.7
Jun 1989		2.825	16.4	6.0	0.50	2.58	1.00	2.2
Jul 1989		1.546	19.2	2.1	0.17	2.00	3.60	1.7
Aug 1989		1.091	20.4	2.3	0.18	1.68	4.00	1.7
Sep 1989		1.508	18.7	4.0	0.75	2.72	2.00	1.8
Oct 1989		1.219	16.5	3.2	0.16	1.33	3.80	1.6
Nov 1989		1.374	12.9	2.8	0.15	1.93	4.60	1.6
Dec 1989		1.212	8.6	2.4	0.14	1.10	1.90	1.5
Jan 1990		1.745	8.2	2.4	0.14	0.94	2.20	1.5
Feb 1990		2.726	8.1	3.1	0.21	1.27	0.90	1.8
Mar 1990		1.425	9.5	4.4	0.18	1.18	1.40	1.5
Apr 1990		1.841	11.1	2.7	0.23	1.01	2.40	1.5
May 1990		1.406	14.2	3.0	0.18	1.23	0.00	1.2
Jun 1990		1.376	17.2	2.2	0.16	1.44	1.14	1.1
Jul 1990		1.961	19.2	3.4	0.20	1.35	5.28	1.6
Aug 1990		1.268	20.3	2.0	0.16	1.49	1.46	1.2
Sep 1990		1.698	19.3	3.4	0.23	1.69	1.04	1.7
Oct 1990		1.918	16.5	3.3	0.35	1.57	1.20	1.4
Nov 1990		1.464	13.5	5.7	0.12	1.26	1.84	1.2
Dec 1990								
Jan 1991		2.180	7.9	2.5	0.26	1.32	0.84	1.5
Summary:	Minimum	1.091	7.6	1.4	0.07	0.94	0.00	1.1
	Maximum	2.825	22.3	6.0	0.75	2.72	5.28	2.2
	Average	1.639	14.1	3.0	0.21	1.55	2.19	1.6
	Limit	NA	NA	12.0	(2)	NA	NA	10.0

Notes:

1. The Brookfield VLR started up in November 1987.
2. The 30-day average effluent ammonia limits are 1.5 mg/l in the summer and 3.0 mg/l in the winter.
3. Blank cells indicate data which was not available.

TABLE 11.
FRIES EFFLUENT MONITORING DATA
(Monthly Averages from DMR Reports)

Month/Year	Flow mgd	BOD_5 mg/l	TSS mg/l
Feb 1988	0.080	73.0	60.0
Mar 1988	0.079	14.7	21.8
Apr 1988	0.090	10.1	17.6
May 1988	0.041	6.3	14.9
Jun 1988	0.048	4.2	11.9
Jul 1988	0.046	9.9	38.7
Aug 1988	0.041	9.2	18.3
Sep 1988	0.042	18.4	24.2
Oct 1988	0.028	9.7	16.2
Nov 1988	0.033	5.9	9.4
Dec 1988	0.033	6.6	7.8
Jan 1989	0.037	5.3	15.3
Feb 1989	0.040	8.8	12.9
Mar 1989	0.029	5.4	5.4
Apr 1989	0.028	4.5	4.2
May 1989	0.045	6.5	7.5
Jun 1989	0.034	6.8	8.7
Jul 1989	0.071	5.8	9.8
Aug 1989	0.039	5.3	9.1
Sep 1989	0.095	6.1	8.9
Oct 1989	0.082	3.8	4.5
Nov 1989	0.073	9.3	11.8
Dec 1989	0.069	9.9	7.9
Jan 1990	0.065	6.8	11.6
Feb 1990	0.112	6.9	8.1
Mar 1990	0.083	3.3	6.8
Apr 1990	0.085	5.4	7.3
May 1990	0.095	5.3	5.6
Jun 1990	0.064	5.5	9.3
Jul 1990	0.032	6.4	12.2
Aug 1990	0.032	6.6	12.9
Sep 1990	0.037	5.9	10.8
Oct 1990	0.090	6.5	11.1
Nov 1990	0.074	5.6	5.5
Dec 1990	0.072	6.9	8.8

TABLE 11.
FRIES EFFLUENT MONITORING DATA
(Monthly Averages from DMR Reports)
(Continued)

Month/Date		Flow mgd	BOD_5 mg/l	TSS mg/l
Jan 1991		0.072	4.3	4.9
Feb 1991		0.094	5.2	5.1
Mar 1991		0.134	3.9	4.5
Apr 1991		0.113	4.3	6.2
Summary:	Minimum	0.028	3.3	4.2
	Maximum	0.134	18.4	38.7
	Average	0.063	6.9	11.0
	Limit	0.220	30.0	30.0

Notes:
1. The Fries VLR began operation on February 22, 1988 and only one BOD/TSS measurement was taken in February, so the data from that month is not included in this summary.

TABLE 12.
BROOKVILLE EFFLUENT MONITORING DATA
(Monthly Averages from Operating Reports)

Month/Year		Flow mgd	Temp °C	TSS mg/l	NH_3-N mg/l	BOD_5 mg/l
Aug 1988		0.485	25.8	7.3	0.67	3.0
Sep 1988		0.543	22.0	6.3	0.07	2.7
Oct 1988		0.529	18.6	6.7	0.43	3.8
Nov 1988		0.809	16.2	14.9	0.60	4.4
Dec 1988		0.640	13.2	8.8	0.49	2.3
Jan 1989		0.970	12.7	13.2	0.09	3.2
Feb 1989		0.821	10.9	10.9	0.13	2.7
Mar 1989		1.068	12.0	11.6	0.56	3.9
Apr 1989		1.213	14.1	8.7	0.64	2.9
May 1989		1.276	15.4	9.3	0.50	6.2
Jun 1989		0.597	19.7	7.1	0.13	3.1
Jul 1989		0.592	23.7	10.8	1.11	4.2
Aug 1989		0.548	22.2	9.1	0.69	4.6
Sep 1989		0.706	21.8	7.6	1.73	4.5
Oct 1989		0.511	18.3	11.3	0.86	4.3
Nov 1989		0.616	16.9	6.4	0.24	6.3
Dec 1989		0.463	12.8	5.4	1.33	4.5
Jan 1990		0.700	11.4	5.9	0.36	8.5
Feb 1990		1.169	12.4	5.3	0.28	6.4
Mar 1990		0.821	13.3	6.7	0.42	7.3
Apr 1990		0.912	14.1	8.7	0.34	6.0
May 1990		1.144	15.5	3.8	0.50	3.1
Jun 1990		0.705	16.8	3.8	0.88	5.9
Jul 1990		0.866	20.1	5.6	0.60	4.0
Aug 1990		0.693	21.9	3.8	0.52	4.1
Sep 1990		0.609	20.3	4.1	0.58	5.0
Oct 1990		0.769	18.7	5.7	0.59	4.6
Nov 1990		0.607	14.6	4.7	0.29	4.4
Dec 1990						
Jan 1991		0.828	12.1	4.4	0.40	2.3
Summary:	Minimum	0.463	10.9	3.8	0.07	2.3
	Maximum	1.276	25.8	14.9	1.73	8.5
	Average	0.766	16.8	7.5	0.55	4.4
	Limit	NA	NA	12.0	1.50	10.0

Notes:

1. The Brookville VLR started up in August 1988.
2. Blank cells indicate data which was not available.

TABLE 13.
HILLSBORO EFFLUENT MONITORING DATA
(Monthly Averages from Operating Reports)

Month/Year		Flow mgd	Temp °C	TSS mg/l	NH_3-N mg/l	P mg/l	BOD_5 mg/l
May 1989		1.272	15.1	31.6	4.65	1.83	20.3
Jun 1989		0.749	19.1	21.1	11.56	1.93	9.0
Jul 1989		0.647	21.5	16.8	13.36	1.32	6.4
Aug 1989		0.755	22.0	15.4	12.99	6.11	2.5
Sep 1989		0.632	20.9	12.0	4.08	5.06	2.1
Oct 1989		0.667	17.3	11.8	0.08	1.77	2.0
Nov 1989		0.656	14.6	9.0	0.28	0.69	2.0
Dec 1989		0.651	10.0	10.5	0.10	0.70	2.0
Jan 1990		0.945	10.3	12.4	0.30	0.44	2.0
Feb 1990		1.209	10.7	13.3	0.05	0.58	2.0
Mar 1990		0.907	12.0	11.6	0.48	0.42	2.1
Apr 1990		0.927	13.3	10.3	0.85	0.61	2.0
May 1990		1.346	15.5	25.3	2.28	2.50	11.9
Jun 1990		0.840	19.2	0.3	1.40	2.15	2.3
Jul 1990		0.600	21.6	6.8	3.51	1.32	2.9
Aug 1990		0.751	21.8	5.4	5.18	1.65	6.8
Sep 1990		0.823	21.1	3.6	4.58	2.05	2.0
Oct 1990		1.151	18.0	4.4	3.31	1.52	2.4
Nov 1990		0.788	15.5	2.3	0.55	1.31	2.0
Dec 1990							
Jan 1991		1.565	10.8	1.8	0.31	0.48	2.4
Summary:	Minimum	0.600	10.0	0.3	0.05	0.42	2.0
	Maximum	1.565	22.0	31.6	13.36	6.11	20.3
	Average	0.894	16.5	11.3	3.49	1.72	4.3
	Limit	NA	NA	12.0	1.50	1.00	10.0

Notes:

1. The Hillsboro VLR started up in May 1989.
2. The Hillsboro VLR was designed for biological phosphorus removal but supplementary alum is added in the final clarifier. The extent of phosphorus removal in the VLR (if any) is not known.
3. Blank cells indicate data which was not available.

TABLE 14
PERFORMANCE DATA FOR BROOKFIELD VLR
DURING A PERIOD OF EXCESS FLOWS

Design flow rate:	1.3 mgd
Flow rate during this period:	4.8 mgd
Design hydraulic retention time:	14.3 hours
HRT during this period:	<1 hour
Design clarifier overflow rate:	331 g/sf-d
Clarifier overflow rate during this period:	1,223 g/sf-d
MLSS concentrations before excess flows:	Tank 1 - 6,200 mg/l Tank 2 - 6,200 mg/l Tank 3 - 6,200 mg/l
MLSS concentrations during this period:	Tank 1 - 7,400 mg/l Tank 2 - 7,400 mg/l Tank 3 - 1,800 mg/l
Effluent concentrations during this period:	BOD 5 mg/l SS 5 mg/l NH_3-N 1.1 mg/l

REFERENCES

1. Performance data for the Brookfield WWTP, the Hillsboro WWTP and the Brookville WWTP provided by the Ohio EPA.

2. Performance data for the Fries WWTP provided by the Virginia Water Control Board.

3. Performance data for the Hohenwald WWTP provided by the Tennessee Department of Conservation.

4. Miscellaneous information provided by Envirex regarding design criteria, budget costs, etc.

5. Brandt, R.A., E.J. Brown, and G.B. Shaw. Innovative Retrofit without Federal Funds; Brookville, Ohio Wastewater Treatment Facilities. Presented at the 63rd Annual Meeting of the Ohio Wastewater Pollution Control Association, June 16, 1989.

6. Site visit to the Hillsboro, OH wastewater treatment plant on April 26, 1991. The treatment plant operator, Gary Davis, was interviewed during this site visit.

SECTION 5
COMPARISON WITH EQUIVALENT TECHNOLOGY

OXIDATION DITCH TECHNOLOGY REVIEW

As stated earlier, the VLR technology is capable of meeting stringent effluent limitations for CBOD, TSS and ammonia-N. The process is further capable of 60 to 80 percent total nitrogen and phosphorus removal.

A comparison of this technology could be made with modified conventional activated sludge systems as well as with proprietary designs for nutrient removal that are capable of the same system performance. It was decided, however, to compare the VLR with a conventional oxidation ditch became of the similarity of process concept. In the late 1970's, there were approximately 650 oxidation ditch installations in the United States and Canada.[1] A typical oxidation ditch flow diagram is shown in Figure 7.

An oxidation ditch is an activated sludge reactor in which the wastewater circulates constantly in a loop. The reactor is typically shown as an oval "racetrack" but many other closed loop configurations are also available. Oxidation ditches can be anywhere between four and sixteen feet deep. Many oxidation ditch designs incorporate sloping sidewalls, although the system being considered uses straight sidewalls.[1,2] The first oxidation ditch of this type in the U.S. began operation in December of 1976. In August of 1990, there were 169 plants in operation which used this type of oxidation ditch, while approximately 69 additional projects were in the design phase or were under construction.[2]

Although a particular oxidation ditch was the source of the majority of the data used in this study, early information from other oxidation ditch designs is also used. This particular oxidation ditch uses low speed, mechanical surface aerators to provide aeration and circulation through the ditch.[2] Other oxidation ditches may use horizontal brush, cage, or disc-type aerators.[1]

PERFORMANCE

Based on random interviews, it was determined that the majority of the operators and supervisors at wastewater treatment plants with oxidation ditches are extremely pleased with the operation and reliability of their systems.[3,4,5] Performance data for ten selected oxidation ditch systems is presented in Table

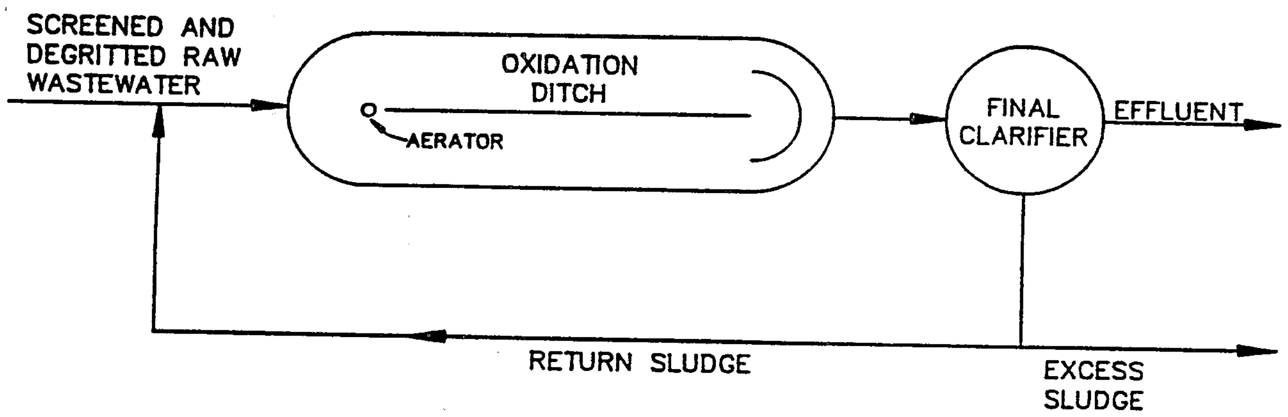

Figure 7
Oxidation Ditch Flow Diagram

15.[2] This data represent well operated and conservatively designed oxidation ditches and reflects the best expected performance.

TABLE 15
OXIDATION DITCH EFFLUENT MONITORING DATA
(Monthly Averages)

Location	Month/Year	Flow mgd	Temp ToC	SS mg/l	NH_3-N mg/l	BOD_5 mg/l	NO_3-N mg/l	TN mg/l
Baraboo, WI	Sep 1983	1.44	18.5	4		5		
	Oct 1983	1.35	16.0	5		5		
	Nov 1983	1.40	13.3	6		5		
	Dec 1983	1.30	8.8	6		8		
	Jan 1984	1.30	7.1	7		11		
	Feb 1984	1.50	7.5	12		11		
Danville, KY	Jul 1981	2.36	23.0	3	1.6	8		
	Aug 1981	2.14	23.0	5	0.4	4		
	Sep 1981	1.98	31.0	5	0.3	6		
	Oct 1981	2.32	19.0	8	0.6	6		
	Nov 1981	2.00	16.0	7	1.0	7		
	Dec 1981	3.06	13.0	15	0.7	13		
Corbin, KY	Oct 1982	1.06		6	2.1	11		
	Nov 1982	1.75		5	1.4	8		
	Dec 1982	2.75		8	1.3	7		
	Jan 1983	2.05		6	1.8	7		
	Feb 1983	2.66		8	1.3	6		
	Mar 1983	2.06		5	1.2	4		
Kemmerer, WY	Sep 1983	0.78		10	0.1	35		
	Oct 1983	0.64	14.0	11	0.3	4		
	Nov 1983	0.64	12.0	7	0.1	5		
	Dec 1983	0.67	9.0	14	0.1	3		
	Jan 1984	0.71	8.0	2	<0.1	2		
	Feb 1984	0.77	8.0	2	<0.1			
Deland, FL	Jun 1981	1.45		5		15		
	Jul 1981	1.50		4	10.0	11	0.06	
	Aug 1981	1.50		3	10.0	12	0.03	
	Sep 1981	1.50		5	3.0	7	0.50	
	Oct 1981	1.60		4	2.0	8	0.40	
	Nov 1981	1.60		4	0.3	7	3.00	
	Dec 1981	1.65		5	10.0	7	0.30	

TABLE 15
OXIDATION DITCH EFFLUENT MONITORING DATA
(Monthly Averages)
(Continued)

Location	Month/Year	Flow mgd	Temp ToC	SS mg/l	NH_3-N mg/l	BOD_5 mg/l	NO_3-N mg/l	TN mg/l
Evanston, WY	Sep 1985	2.10	16.0	6	0	7		
	Oct 1985	2.00	14.0	7	0	5		
	Nov 1985	1.90	11.5	5	0	4		
	Dec 1985	2.00	8.5	8	0	5		
	Jan 1986	2.00	8.0	10	0	7		
	Feb 1986	2.60	7.5	9	0	8		
	Mar 1986	2.40	8.5	6	0	6		
Belle Glade, FL	Jan 1986			6.9	0.4	6.3		13.1
	Feb 1986			3.8	0.1	8.6		10.5
	Mar 1986			6.6	0.2	10.0		11.6
	Apr 1986			4.6	0.2	12.2		9.3
	May 1986			3.0	0.1	11.3		4.5
	Jun 1986			3.3	0.1	7.3		6.0
	Jul 1986			4.2	0.2	3.5		9.0
	Aug 1986			2.6	0.4	2.6		12.7
	Sep 1986			2.4	0.3	2.7		11.0
	Oct 1986			3.8	0.3	3.3		9.4
	Nov 1986			2.8	0.2	3.2		3.8
	Dec 1986			3.6	0.1	2.7		5.6
Smyrna, TN	Sep 1985	1.7		1.6	0.1	1.9		
	Oct 1985	1.7		2.4	0.1	2.2		
	Nov 1985	1.7		2.7	0.2	2.3		
	Dec 1985	1.6		3.5	0.2	3.0		
	Jan 1986	1.6		3.3	0.3	4.0		
	Feb 1986	1.8		3.7	0.1	2.4		
Bradenton, FL	Jan 1987	3.7		6		8		4.8
	Feb 1987	3.7		6		8		6.7
	Mar 1987	4.7		12		10		9.5
	Apr 1987	4.8		11		10		5.2
	May 1987	3.9		9		10		6.4

TABLE 15
OXIDATION DITCH EFFLUENT MONITORING DATA
(Monthly Averages)
(Continued)

Location	Month/Year	Flow mgd	Temp ToC	SS mg/l	NH_3-N mg/l	BOD_5 mg/l	NO_3-N mg/l	TN mg/l
Bernards Twp, NJ	Jan 1985	0.86	8.5	4.6	0.19	3.1		
	Feb 1985	1.05	8.8	2.9	0.34	4.1		
	Mar 1985	0.92	10.5	2.8	0.34	3.1		
	Apr 1985	0.75	14.0	10.0	0.80	3.8		
	May 1985	1.00	17.0	6.0	0.78	3.1		
	Jun 1985	0.85	18.9	9.0	0.69	3.0		
	Jul 1985	0.78	21.7	7.6	0.76	3.0		
	Aug 1985	0.78	21.5	4.4	0.68	2.0		
	Sep 1985	0.98	20.6	4.5	0.33	2.3		
Hayden Lake, ID	Oct 1988	0.17		6		6		
	Nov 1988	0.18		4		4		
	Dec 1988	0.19		5		3		
	Jan 1989	0.22		6		3		
	Feb 1989	0.26		7		3		

The performances of five VLR systems are summarized in Tables 9 through 13 and discussed in Section 4. A comparison of the performance data from the two technologies indicates comparable results for CBOD, TSS and NH_3-N removal. Less data were available on total nitrogen or phosphorus removal for the oxidation ditches since these plants were not designed for nutrient control.

COSTS

Budget costs for oxidation ditch systems are provided in Table 16. Construction cost data from the first quarter of 1983 was used in the preparation of this table and was provided by the manufacturer of this oxidation ditch.[2] The 1983 costs were adjusted to current values through the ENR U.S. 20-city average construction index (4006 for March 1983; 4772.65 for February 1991). The 1991 budget cost information is also represented in graphical form in Figure 8.

The budget costs given in Table 16 are both construction costs and capital costs. Construction costs include dewatering, site work and buildings; capital costs include dewatering, site work, buildings, engineering fees, construction supervision and contingencies. The construction costs were provided by an oxidation ditch manufacturer, as mentioned in the previous paragraph. The reactor costs shown in this table were taken as 30 percent of the total plant capital cost.

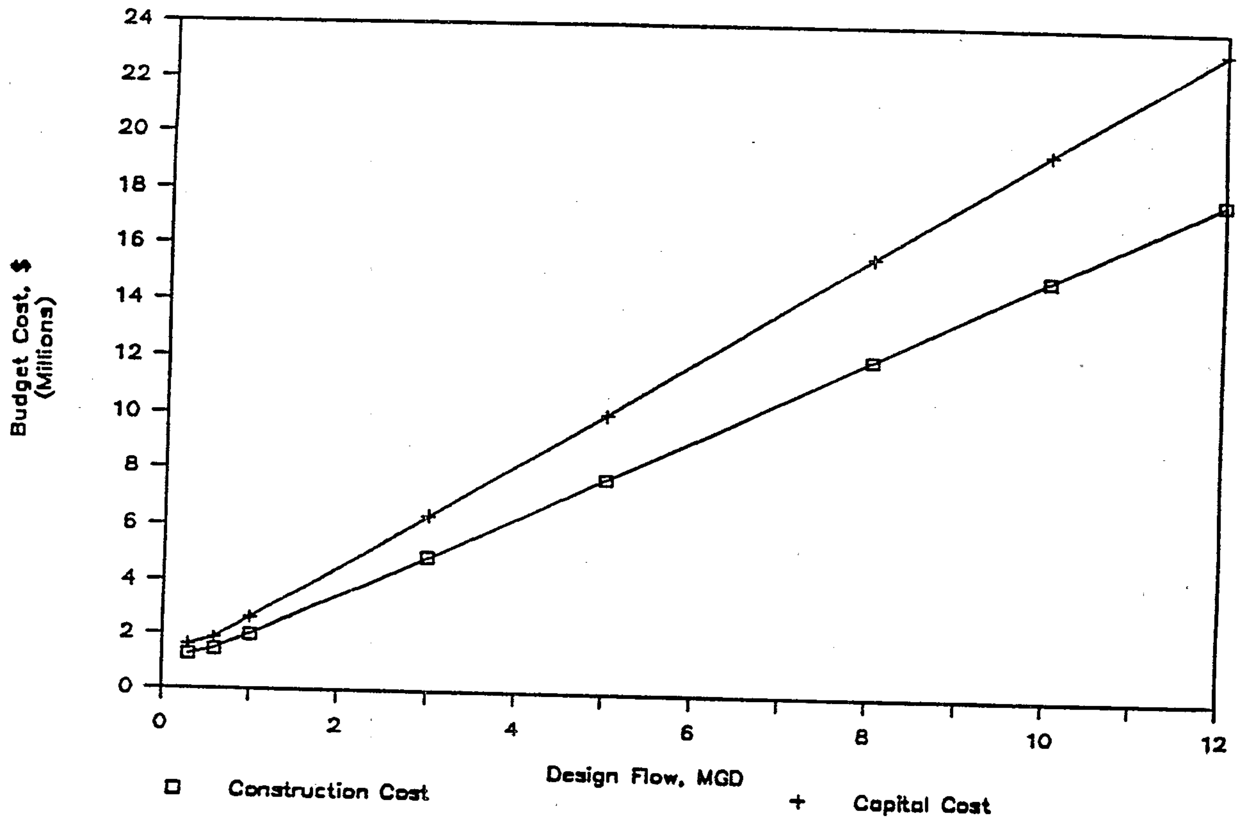

Figure 8
Carrousel Oxidation Ditch Budget Costs

TABLE 16
APPROXIMATE BUDGET COSTS FOR CARROUSEL OXIDATION DITCHES

Design Flow mgd	Total Plant		Reactor Capital Cost, $
	Construction Cost, $	Capital Cost, $	
0.3	1,250,944	1,626,227	487,868
0.6	1,451,095	1,886,424	565,927
1.0	2,025,338	2,632,940	798,882
3.0	4,896,553	6,365,519	1,909,655
5.0	7,743,940	10,067,122	3,020,136
8.0	12,104,374	15,735,687	4,720,706
10.0	15,011,331	19,514,730	5,854,419
12.0	17,870,632	23,231,821	6,969,546

The 30 percent value was obtained from a detailed breakdown of oxidation ditch plant costs developed in reference.[6] Capital costs were estimated from construction costs. The total cost for engineering and construction supervision was assumed to be 15 percent of the construction costs. Fifteen percent of the construction cost was also added for contingencies.

A side-by-side comparison of total VLR plant costs versus. total oxidation ditch plant costs are difficult to make because of the variation in total plant costs due to site specific factors for those plants where data was available. Budget construction cost and capital cost data for VLRs are shown in Table 17, and a cost curve is shown in Figure 9. These costs were quoted by a representative of the VLR manufacturer in March of 1991.[7] Note that the VLR costs are for the reactors only.

The comparison of reactor cost (concrete plus miscellaneous metal) shown in Tables 16 and 17 provide the best judgement as to an overall process cost comparison. This comparison indicates a VLR reactor cost is approximately 23 percent less than a comparable oxidation ditch plant at 1.0 mgd. The VLR cost became significantly less expensive at the higher design flows.

A separate comparison of in-place concrete cost for equal volume VLR and oxidation aerators was made as a part of this analysis. A 20 foot aeration basin was used for the VLR and a 10 foot depth was used for the oxidation ditch. The in place concrete cost for a 120,000 cu.ft. reactor (approximately 2.0 mgd design flow) showed the VLR reactor to be 29.7 percent less costly than the oxidation ditch. In this analysis, excavation costs were assumed to be the same for both designs. As mentioned earlier, the possibility of increased rock excavation cost

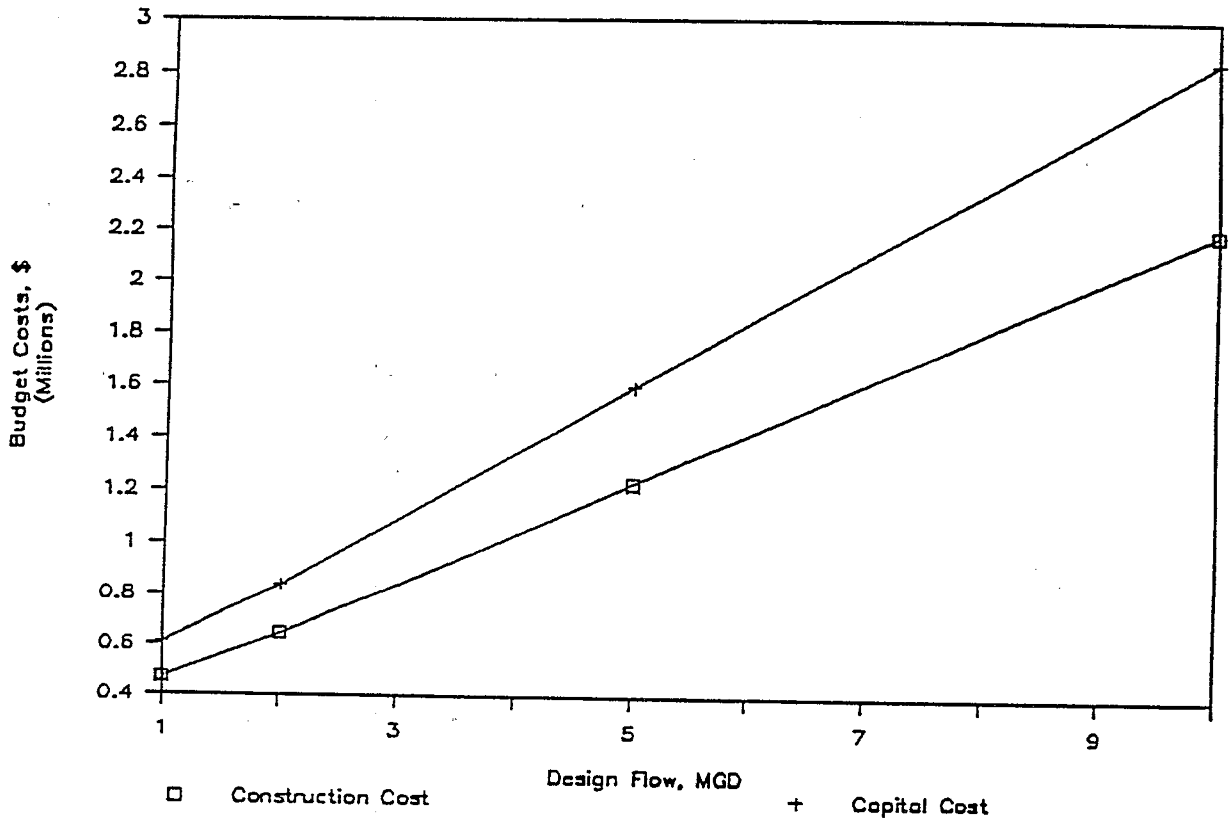

Figure 9
VLR Reactor Budget Costs

for VLR designs may increase the cost of VLR reactors at locations where the plant hydraulic profile dictates greater depths.

TABLE 17
BUDGET COSTS FOR VERTICAL LOOP REACTORS

Flow mgd	Construction Cost, $	Capital Cost, $
1.0	470,000	611,000
2.0	646,000	839,800
5.0	1,231,000	1,600,000
10.0	2,193,000	2,850,900

Notes:

1. Construction costs based on information provided by Envirex, Inc.
2. Construction costs include equipment, concrete divider, blower, concrete and installation.
3. Capital costs calculated from construction costs using the following factors: engineering and construction supervision = 15 percent of construction cost; contingencies = 15 percent of construction cost.
4. Capital costs include equipment, concrete divider, blower, concrete, installation, engineering, construction supervision and contingencies.

The only facility which provided a detailed construction cost for a treatment plant which incorporated the VLR technology was the Brookfield WWTP. The Brookfield WWTP was very nearly a new plant including new preliminary and secondary treatment facilities, chlorination/dechlorination facilities, and secondary control and maintenance buildings. Two existing anaerobic digesters were retrofitted to form an aerobic digester and a sludge holding tank. The total construction cost was approximately $5,575,000 for this 1.3 mgd facility.[8]

Cost data were also available for a VLR facility that was installed as a retrofit of existing basins. Design engineers for the Brookville WWTP estimated that the capital cost for converting three existing aeration basins to VLRs would be $1,475,000 (in 1987-1988). A cost-effectiveness analysis that compared the VLR retrofit to a completely mixed activated sludge retrofit was developed by the design engineers. Both capital and operating costs were considered. The completely mixed activated sludge system was determined to be 4 percent more expensive than the VLR system.[9]

OPERATION AND MAINTENANCE

Operating costs for both VLRs and oxidation ditches are primarily made up of labor and utility costs. All plant personnel interviewed stated that they did not use chemicals in their oxidation ditches or VLRs, and that costs for maintenance materials were similar.[3,4,5,10,11,12,13,14]

Labor Requirements

VLR operators reported operating labor requirements of 9 to 27 hours per week for VLR operation and maintenance. Typical tasks for both VLRs and oxidation ditches included daily dissolved oxygen concentration measurements, oil changes and minor cleaning and repair (i.e. remove large solids such as pieces of cloth, etc. from aerators).[3,4,5,10,11,12,13,14] The above estimate of operating labor did not include blower maintenance or major repair or replacement of blower, motors, disc aerators or pumps.

This information indicates that VLRs may require more labor than oxidation ditches. When comparing the labor requirements, however, it must be noted that the VLR operators included sample analysis time in their labor estimates, while the oxidation ditch labor estimate does not appear to include this task.

Utility Requirements

Process aeration efficiency is the primary factor influencing the utility requirements for both oxidation ditches and VLRs. During the evaluation of the VLR, designs provided by the VLR manufacturer and by an oxidation ditch manufacturer were compared. Based on standard oxygen requirements (SOR's), the VLR was designed for 3.4 pounds of oxygen per brake horsepower-hour, while the oxidation ditch was designed for 3.5 pounds of oxygen per brake horsepower-hour.[2,7]

In both the VLR and oxidation ditch plants, the installed aeration horsepower is typically 20 to 30 percent greater than the peak oxygen demand. the aeration energy requirements typically vary from a low of 20 percent to a high of 70 percent of total plant energy requirements depending on influent and interprocess pumping, type of digestion employed and other appurtenant equipment. A survey of total plant energy requirements has little if any value in comparing the aeration efficiency of VLRs compared to oxidation ditches. Of the seven plants included in this survey, it was not possible to separate aeration energy from total plant requirements for VLRs.

Our assessment of available data including a survey of the energy usage from 21 oxidation ditch plants along with test data submitted to USEPA for qualifyingVLRs as "Innovative Technology" suggest that there is less than 10 percent difference in the aeration requirements of VLRs versus. oxidation ditches.[6]

Both technologies employ similar surface or brush aerators. The VLR adds course bubble diffused air beneath the horizontal baffle to increase aeration efficiency. both technologies can utilize the denitrification energy credit. The VLR manufacturer publicizes this feature to a much greater extent than the oxidation ditch manufacturer.

A survey of the energy use of 21 oxidation ditch plants showed approximately 20 percent reduction in total plant energy needs for plants designed for nitrogen removal versus those designed for nitrification.[6] In this same survey of oxidation ditches, the total plant energy usage varied from a low of 296,000 kwh per year per mgd to a high of 740,000 kwh per year per mgd.

The installed HP for VLRs is somewhat lower than the average value used for oxidation ditches. Oxidation ditches are commonly designed for 50 to 60 HP per million gallons of flow. this is compared to 35 to 45 HP per million recommended gallons used by the current VLR designs.

Three of the existing VLRs (Hohenwald, Fries and Hillsboro) received USEPA funding based on innovative technology designations.[15] In order to be designated innovative, a technology must meet the following criteria established by the United States Environmental Protection Agency (USEPA): the technology must be one which has not been fully proven and which can demonstrate 1) life cycle cost savings of at least 15 percent, 2) energy savings of at least 20 percent, or 3) significant environmental or operational benefits over conventional technology. The innovative technology designations given to the Hillsboro, Hohenwald and Fries wastewater treatment plants were based on projected energy savings of at least 20 percent.[7,15]

Brookfield applied to the Ohio EPA and the USEPA Region V for an innovative technology designation. The most recent submission by the design engineer was based on operational data and stated that the Brookfield wastewater treatment plant demonstrated energy savings of 22.7 percent over a wastewater treatment plant with a conventional activated sludge (CAS) system using fine bubble diffusers.[15]

However, Region V assessment of the operating data indicated that the energy savings of the VLR over the CAS system were no more than 8.2 percent. Other statements made by the EPA were more qualitative and could not be associated with exact quantities of energy, so it is impossible to place an exact value on the energy savings of the VLR over the CAS system (if any).

The request submitted by the Hillsboro design engineer concluded that the energy requirements for the Hillsboro VLR system were approximately 25 percent less that the requirements for a comparable single stage aeration process, while the reevaluation performed by the Ohio EPA indicated a projected energy savings of approximately 5 percent.[16]

LAND AREA

Because the depth of a VLR may be as much as twice the depth of an oxidation ditch designed for a similar flow, the land area required for a VLR is significantly less than that required for an oxidation ditch of the same capacity. The land area requirements for nine VLR systems and seven oxidation ditch aeration basins are shown in Table 18.[2,7]

TABLE 18
LAND AREA REQUIREMENTS
(Vertical Loop Reactor Versus Carrousel Oxidation Ditch)

Flow mgd	Area sq. ft.	Depth ft.[2]	Dimensions ft. (Number of Basins)	BOD Removed lb/day	NH_3-N Removed lb/day	Loading gpd/sf	Loading lbs BOD/sf-d
VERTICAL LOOP REACTOR:							
0.220	2,480	12.0	62' x 20' x 12' deep (2)	396	0	88.7	0.160
0.645	5,427	10.7	60.3' x 30' x 10.7' deep (3)	807	100	118.9	0.149
0.850[1]	6,375	13.5	127.5' x 20' (1) & 127.5' x 15' (2)	1361	162	133.3	0.214
1.000	7,250	20.8	125' x 29' x 20.8' deep (2)	2252	105	137.9	0.311
1.100	5,673	16.0	141.8' x 20' (1) & 141.8' x 10' (2)			193.9	
1.300	5,150	19.8	128.8' x 29' (1) & 128.8' x 10' (2)	1301	146	252.4	0.253
3.000	15,912	21.2	102' x 26' x 21.2' deep (6)			188.5	
4.500[1]	14,964	20.0	129' x 29' x 20' deep (4)	6192	357	300.7	0.414
5.000	13,400	20.0	112' x 20' x 20' deep (6)	8757	1022	372.0	0.652
Average						198.5	0.307
OXIDATION DITCH:							
0.100	1,529	6.25	68.17' x 25' x 6. deep	192	24	65.4	0.125
0.100[1]	2,215	5.5-7.25	Complicated	192	24	45.1	0.087
0.140	2,879	6.5	77.33' diameter x 6.5' deep	222	34	48.6	0.077
0.150	3,085	6.5	77.17' diameter x 6.5' deep	238	49	48.6	0.077
0.800	15,773	10.0	213' x 84' x 10' deep	1635	267	50.7	0.104
1.000	8,822	10.0	120.5' x 42.67' x 10' deep (2)	1376	325	113.3	0.156
3.200	17,742	11.0	118' x 92' x 11' deep (2)	5071	0	180.4	0.286
Average						78.9	0.130

Notes:
1. Systems marked with an asterisk are designed for phosphorus removal.
2. Average depth for two or more basins.

A comparison of the average loadings in lbs BOD removed per square foot of reactor shown in Table 18 indicates that the land area required for an oxidation ditch is approximately 2.5 times the area required for a VLR designed for the same flow rate. The smaller land area required for the VLR may be offset, however, by the deeper tank design which is more likely to require rock excavation.

REFERENCES

1. Innovative and Alternative Technology Assessment Manual. Office of Water Program Operations, Washington D.C. and Office of Research and Development, Cincinnati, OH, U.S. Environmental Protection Agency. February, 1980.

2. Telephone conversations and correspondence with Eimco representatives during March of 1991.

3. Telephone conversation with Cary, IL treatment plant operator (Cary uses a Carrousel oxidation ditch).

4. Telephone conversation with Bradenton, FL treatment plant operator (Bradenton uses a Carrousel oxidation ditch).

5. Telephone conversation with East Chicago, In treatment plant operator (East Chicago uses a Carrousel oxidation ditch).

6. A comparison of oxidation ditch plants to competing processes for secondary and advanced treatment of Municipal Wastes; EPA 600/2-78-051, March 1978.

7. Telephone conversations and correspondence with George Smith of Envirex during March, April, May and June of 1991.

8. Floyd Browne Associates, Inc. Performance Certification Report. Submitted to Trumbull County on April 29, 1989.

9. Brandt, R.A., E.J. Brown, and G.B. Shaw. Innovative Retrofit without Federal Funds: Brookville, Ohio Wastewater Treatment Facilities. Presented at the 63rd Annual Meeting of the Ohio Wastewater Pollution Control Association, June 16, 1989.

10. Site visit to the Brookville, OH wastewater treatment plant on April 19, 1991. During this visit, Ron Brandt and Jon Weist were interviewed. Mr. Brandt is the Brookville WWTP operator; Mr. Weist is his assistant.

11. Site visit to the Hillsboro, OH wastewater treatment plant on April 26, 1991. The treatment plant operator, Gary Davis, was interviewed during this site visit.

12. Site visit to the Brookfield, OH wastewater treatment plant on May 15, 1991. The treatment plant operator, Daniel Earhart, was interviewed during this site visit.

13. Telephone interview of Paul Webb on April 18, 1991. Mr. Webb is the Hohenwald, TN wastewater treatment plant operator.

14. Telephone interview of Eugene Graham on April 18, 1991. Mr. Graham is the Fries, VA wastewater treatment plant operator.

15. Floyd Browne Associates, Inc. Report submitted to prove that the Brookfield VLR deserved innovative funding. Submitted to Trumbull County on February 15, 1989.

16. Letter to the City of Hillsboro from the Ohio EPA. This letter informed the City that the Ohio EPA was withdrawing its innovative technology designation of the Hillsboro VLR system.

17. Report and Recommendation prepared by the USEPA Region V in response to Brookfield's request for designation as an innovative technology.

SECTION 6
NATIONAL IMPACT ASSESSMENT

The development of the VLR adds another competing activated sludge biological process to the existing technologies. Its advancement will add to the existing alternatives and will help encourage all treatment technologies to remain competitive in terms of capital costs, operating costs and effluent levels.

Similarly, the costs of conventional systems will help keep the VLR competitive. Note, however, that the price stability of a single-vendor supplied proprietary technology such as the VLR is more volatile than the price of a technology marketed by multiple vendors.

Based on existing information, it is likely that the VLR technology will be well-accepted by wastewater treatment professionals, particularly because it is possible to retrofit existing basins to serve as VLRs.

The proven applications of VLR systems are many and include BOD removal, nitrification and denitrification. Phosphorus removal may be a valid application as well, but no significant data is currently available.