Chapter 5
Innovative PACT Activated Sludge, CAPTOR Activated Sludge, Activated Bio-Filter, Vertical Loop Reactor, and PhoStrip Processes

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Acronyms

ABF	Activated bio-filters
BOD	Biochemical oxygen demand
CAST	CAPTOR in activated sludge treatment
CBOD	Carbonaceous biochemical oxygen demand
COD	Chemical oxygen demand
DAF	Dissolved air flotation
F/M ratio	Food-to-microorganism ratio
HRT	Hydraulic retention time, d
MF	Membrane filters
MG	Million gallons
MGD	Million gallons per day
MLSS	Mixed liquor suspended solids
NH_3-N	Ammonia nitrogen
NO_2-N	Nitrite nitrogen
NO_3-N	Nitrate nitrogen
NSFC	National Small Flows Clearinghouse
PAC	Powdered activated carbon
PACE	Effluent PAC concentration, mg/L
PACI	Influent PAC concentration, mg/L
PACR	Mixed liquor PAC concentration in the reactor, mg/L

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PACT	Powdered Activated Carbon Treatment
SRT	Design solids retention time, d
TKN	Total Kjeldahl nitrogen
TSS	Total suspended solids
UMIST	University of Manchester Institute of Science and Technology
UNIDO	United Nations Industrial Development Organization
USACE	US Army Corps of Engineers
USEPA	US Environmental Protection Agency
VLR	Vertical Loop Reactor
WRC	British Water Research Centre

5.1 Powdered Activated Carbon Treatment (PACT)

5.1.1 Types of PACT Systems

The powdered activated carbon (PAC) activated sludge system is a process modification of the activated sludge process. PAC is added to the aeration tank where it is mixed with the biological solids (Fig. 5.1). The mixed liquor solids are settled and separated from the treated effluent. In a gravity clarifier, polyelectrolyte will normally be added prior to the clarification step to enhance solids-liquid separation. If phosphorus removal is necessary, alum is often added at this point also. Even with polyelectrolyte addition, tertiary filtration is normally required to reduce the level of effluent suspended solids. The clarifier underflow solids are continuously returned to the aeration tank. A portion of the carbon-biomass mixture is wasted periodically to maintain the desired solids inventory in the system.

There are six types of combined biological and physicochemical PAC process systems [1–7]:

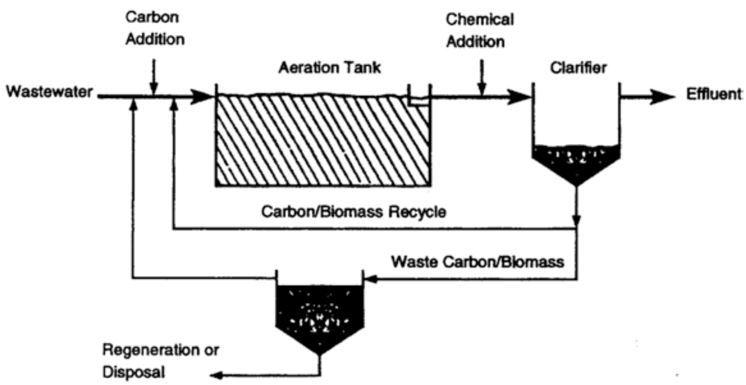

Fig. 5.1 Powdered activated carbon activated sludge process (PACT) [10, 14]

(a) Continuous combined biological and physicochemical PAC process systems involving the use of sedimentation clarifiers
(b) Combined biological and physicochemical PAC sequencing batch reactor systems involving the use of sedimentation clarifiers
(c) Continuous combined biological and physicochemical PAC process systems involving the use of dissolved air flotation (DAF) clarifiers
(d) Combined biological and physicochemical PAC sequencing batch reactor systems involving the use of DAF clarifiers
(e) Continuous combined biological and physicochemical PAC process systems involving the use of membrane filters (MF)
(f) Combined biological and physicochemical PAC sequencing batch reactor involving the use of membrane filters (MF)

When PAC is dosed into an activated sludge process for combined adsorption and biochemical reactions, the combined process is also called the PACT process, in which PAC still stands for powdered activated carbon, while ACT stands for activated sludge.

5.1.2 Applications and Performance

The addition of PAC to plug flow and complete mix suspended growth reactors is a more common process modification for industrial wastewater treatment than for municipal systems. Demonstrated advantages of PAC addition to suspended growth reactors include [8]:

(a) Improved solids settling and dewatering characteristics
(b) The ability of PAC to adsorb biorefractory materials and inhibitory compounds
(c) Improving effluent quality and reducing the impact of organic shock loads
(d) Reduction in odor, foaming, and sludge bulking
(e) Improved color and 5-day BOD removal

Because PAC is wasted with excess biomass, virgin or regenerated PAC addition is required to maintain the desired concentration in the biological reactor. This can represent a significant cost factor for the system. When carbon addition requirements exceed 900–1800 kg/day (2400–4000 lb/day), wet air oxidation/regeneration (WAR) is claimed to represent an economical approach to carbon recovery and waste biomass destruction [9]. However, an ash separation step is needed in this case, affecting the economics of carbon regeneration and recovery [10]. The economic analysis is further clouded by the inability to analytically differentiate powdered carbon from background refractory volatile materials, thus making it difficult to quantify the value of the volatile suspended material recovered after WAR. Although ash separation processes have been reported to be effective in at least two municipal PAC activated sludge plants, the economics of complete PAC/WAR systems relative to other activated sludge nitrification systems are unclear [7, 10, 11].

In the United States, PACT systems for nitrification generally have been applied at municipal treatment plants where industrial sources contribute a significant fraction of the incoming wastewater. In all instances, PAC regeneration was included in the flowsheet [12]. A summary of selected municipal PACT facilities is presented in Table 5.1.

The procedure to follow in designing PACT systems for nitrification involves a modification to those for complete mix or conventional plug flow systems in order to account for the effects of the addition of PAC [13]. According to the major supplier of the technology [12, 14], most PAC process systems are designed at MLSS concentrations of approximately 15 g/L. The mixed liquor is composed of volatile activated carbon, biomass, nonvolatile PAC ash, biomass decay components, and influent inert material. The relative proportions of these materials are strongly influenced by whether carbon regeneration via wet air oxidation and a return of this material to the aerator is practiced. The intent is to maintain the PAC concentration at approximately 1.5 times the biomass level in nitrification PAC reactors [12, 14]. The most appropriate PAC concentration will be dictated by the specific wastewater characteristics and often cannot be specified without bench- or pilot-scale studies. The PAC concentration to be added will depend on the design solids retention time, the hydraulic retention time, and the required PAC concentration in the reactor. According to the US Environmental Protection Agency [14], for practical engineering design considering the loss, the PAC concentration to be added can be calculated from Eq. (5.1):

Table 5.1 Summary of PACT process systems using wet air oxidation for APC regeneration [10, 14]

Facility	Current/design flow, m^3/s	PAC/WAR[a] status	Reason for PAC[a]	Permit limits		
				BOD_5, mg/L	TSS, mg/L	NH_4^+-N, mg/L
Vemon, CT	0.18/0.28	MA	C	10	20	–
Mt. Holly, NJ	0.11/0.22	MA	C,S	30	30	20
E. Burlington, NC	0.31/0.53	MA	C,N,T	12–24	30	4.0–8.0
S. Burlington, NC	0.30/0.42	AS	C,N,T	12–24	30	4.0–8.0
Kalamazoo, MI	1.1/2.4	MA	C,N,T	7–30	20–30	2.0–10.0
Bedford Hts., OH	0.15/0.15	NAC	N,S	10	12	5.1
Medina Co., OH	0.31/0.44	MA	N	10	12	1.5–8.0
N. Olmsted,[b] OH	0.26/0.31	AS	N,S	30	30	2.3–6.9
Sauget, IL	0.70/1.2	AS	T	20	25	–
El Paso, TX	0.20/0.44	MA	N,O	SD[d]	SD	SD

[a] C = Color Removal; S = Space; N = Nitrification; T = Toxics; O = Organics
[b] Plan to convert to NAC without regeneration
[c] MA = Modified operation and/or design for ash control. AS = Converted to conventional activated sludge. NAC = Converted to the use of nonactivated carbon without regeneration

$$\text{PACI} = \text{PACE} + \left(\text{PACR}\right)\text{HRT} / \text{SRT} \tag{5.1}$$

where

PACI is the influent PAC concentration, mg/L
PACR is the mixed liquor PAC concentration in the reactor, mg/L
PACE is the effluent PAC concentration, mg/L
HRT is the hydraulic retention time, day
SRT is the design solids retention time, day

The value of PACE in Eq. (5.1) can be estimated by assuming that the carbon fraction in the effluent TSS (total suspended solids) is the same as the fraction of PAC in the MLSS (mixed liquor suspended solids).

PACT nitrification systems are normally selected when the municipal wastewater contains compounds originating from industrial operations, as stated previously. Nitrifiers are susceptible to a number of organic and inorganic inhibitors found in many industrial wastewaters [14]. Researchers have provided evidence that the addition of PAC to nitrifying activated sludge systems receiving industrial wastewaters improved nitrification rates [14–16]. More recent studies have been completed with the goal of determining the mechanism of nitrification enhancement in PAC activated sludge systems in the presence of adsorbable and nonadsorbable inhibitors [17]. The results indicated that the addition of the proper amount of PAC can completely nullify the toxic effects of an adsorbable nitrification inhibitor. A minor positive effect on nitrification rates was observed when PAC was added to a nitrifying activated sludge system receiving nonadsorbable inhibitors. The activated sludge used in these studies was not acclimated to the inhibiting compounds. Another possible contributing factor to the enhancement of nitrification could be attributed to the fact that the addition of PAC provides particulate matter for attachment of the nitrifying microorganisms, thereby promoting nitrification [18].

5.1.3 Process Equipment

PAC can be fed in the dry state using volumetric or gravimetric feeders or can be fed in slurry form. There are more than 3 major PAC producers, over 50 manufacturers of volumetric and gravimetric feeders, and over 50 manufacturers of slurry feeders [19–21]. There are also many manufacturers of sequencing batch reactors (SBR) [2], dissolved air flotation (DAF) clarifiers [7], and membrane filtration (MF) reactors [6].

5.1.4 Process Limitations

The process limitations of PACT process systems are identical to that of the PAC physicochemical process. The PACT process will increase the amount of generated sludge. Regeneration will be necessary at higher dosages in order to maintain reasonable costs. Most systems will require post-filtration to capture any residual carbon particles. Some sort of flocculating agent such as an organic polyelectrolyte is usually required to maintain efficient solids capture in the clarifier.

About 1 pound of dry sludge will be generated per pound of carbon added. If regeneration is practiced, carbon sludge is reactivated and reused with only a small portion removed to prevent the buildup of inert material. PAC physicochemical process systems are reasonably reliable. In fact, PAC systems can be used to improve process reliability of existing systems.

Additional information on carbon adsorption and combined biological and physicochemical PACT process systems can be found in Refs. [22–31].

5.2 Carrier-Activated Sludge Processes (CAPTOR and CAST Systems)

There has been a substantial interest in recent years in the potential benefits of high biomass wastewater treatment. The major obstacle for achieving this has been the inability of biosolids separation in secondary clarifiers. For the most part, this has been overcome by using various forms of support media or carriers that have the ability to attach high concentrations of aerobic bacterial growth [32–34]. The increase in immobilized biomass reduces the process dependence on secondary settling basins for clarification. In such hybrid systems where attached growth coexists with suspended growth, one gets more stable systems which possess the combined advantages of both fixed and suspended growth reactors.

5.2.1 Advantages of Biomass Carrier Systems

The performance of carrier systems is dependent on the amount of attached biomass, the characteristics of attached and suspended microorganisms, and the type of carriers. The advantages of such hybrid systems are:

(a) Heterogeneity of the microbial population. This is brought about by the differences in the microhabitat of organisms attached to the surface of a carrier and those in the bulk of the solution with respect to pH, ionic strength, and concentration of organics [35–39].

(b) Increased persistence in reactor. This leads to an increase in biomass of organisms, reduction of hydraulic retention time, and thus smaller reactor volumes [40–42].
(c) Higher growth rate [43–45].
(d) Increased metabolic activity. This leads to an increase in respiration and substrate utilization, hence higher removal rates [46–49].
(e) Better resistance to toxicity [50–53].

5.2.2 The CAPTOR Process

One interesting concept of hybrid systems is the CAPTOR process developed jointly by the University of Manchester Institute of Science and Technology (UMIST) and Simon-Hartley, Ltd., in the United Kingdom. This high biomass approach uses small reticulated polyurethane pads as the bacterial growth medium [54]. The pads are added to standard activated sludge aeration reactor, and the system is operated without sludge recycle, essentially combining suspended growth with a fixed film in one process. Excess growth is removed from the pads by periodically passing them through specially designed pressure rollers.

The British Water Research Centre (WRC) and Severn Trent Water Authority conducted a full-scale evaluation of the CAPTOR process for upgrading the activated sludge plant at the Freehold Sewage Treatment Works, in the West Midlands area of England, to achieve year-round nitrification. This full-scale study was jointly sponsored by the US Environmental Protection Agency [55, 56].

5.2.3 Development of CAPTOR Process

As mentioned earlier, the CAPTOR process originated from research work on pure systems in the Chemical Engineering Department of UMIST. Single strands of stainless steel wire were woven into a knitted formation and then crushed into a sphere of about 6 mm (0.25 in.) diameter. These particles of known surface area were used for modeling liquid-fluidized bed systems. From this work derived the idea of using porous support pads for growing biomass at high concentrations that could be used in wastewater treatment systems. The idea was jointly developed and patented by UMIST and their industrial partner Simon-Hartley, Ltd. The present form of the CAPTOR process uses 25 mm × 25 mm × 12 mm (1 in. × 1 in. × 0.5 in.) reticulated polyether foam pads containing pores nominally of about 0.5–0.9 mm (0.02–0.035 in.) diameter and 94% free space [57–59].

5.2.4 Pilot-Plant Study

The conducted pilot-plant work indicated that it was possible to achieve the following [55, 56]:

(a) Biomass concentrations of 7000–10,000 mg/L
(b) Waste sludge concentrations of 4–6% dry solids using a special pad cleaner
(c) Improved oxygen transfer efficiencies
(d) High BOD volumetric removal rates

5.2.5 Full-Scale Study of CAPTOR and CAST

The full-scale evaluation of the CAPTOR process was undertaken at the Freehold Sewage Treatment Works near Stourbridge, West Midlands. The Freehold plant did not achieve any nitrification in the winter and only partial nitrification in the summer. Freehold's activated sludge system consisted of five trains equipped with tapered fine bubble dome diffusers arranged in a grid configuration. The system was modified as shown in Fig. 5.2 to split the wastewater flow into two equal volumes. Half went to two trains that were modified by adding CAPTOR pads to the first quarter of two aeration basins, and the other half went to two trains that remained unaltered and served as a control. The CAPTOR modified trains were each equipped with a CAPTOR pad cleaner (Fig. 5.3), and the CAPTOR pads were prevented from escaping into the remainder of the experimental system aeration basins by screens placed at the effluent ends of the CAPTOR zones.

The Simon-Hartley design predicted that, with a concentration of 40 pads/L, an annual average removal of 75% of the BOD_5 coming into the plant could be achieved in the CAPTOR zones, resulting in a reduced food-to-microorganism (F/M) loading on the follow-on activated sludge stage of 0.08 kg BOD_5/day/kg MLSS. With the

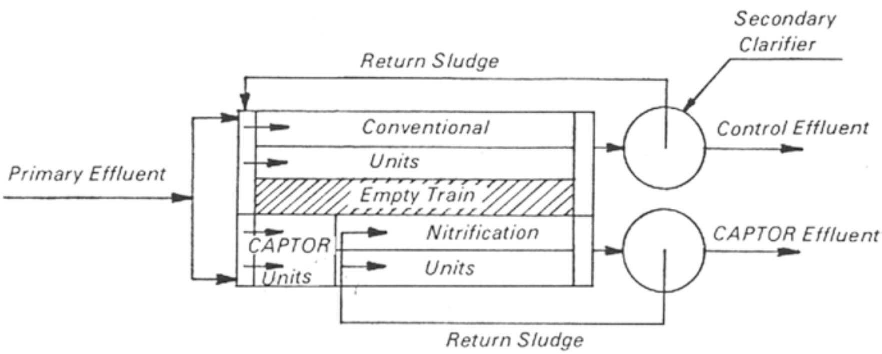

Fig. 5.2 Schematic of treatment plant showing incorporation of CAPTOR [56]

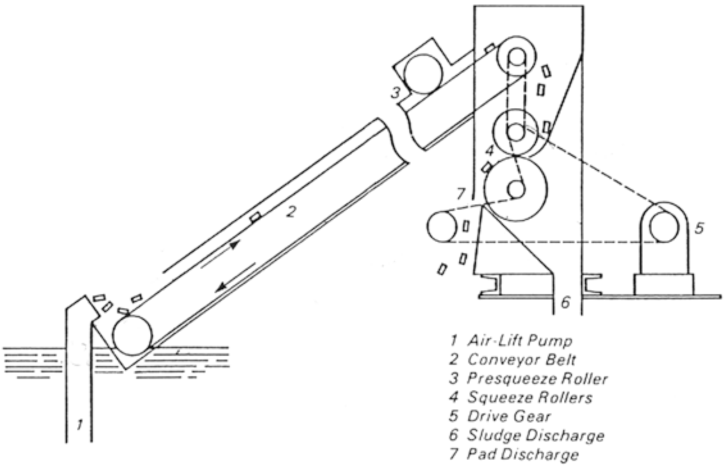

Fig. 5.3 CAPTOR pad cleaner [56]

reduced load, it was predicted that the modified system would achieve year-round nitrification with an effluent ammonia nitrogen concentration of 5 mg/L or less [56].

5.2.5.1 Full-Scale Plant Initial Results

The Freehold modified CAPTOR activated sludge system was put in operation and immediately encountered a major problem. The CAPTOR pads floated on the surface of the tanks and would not become incorporated into the tank liquor. A solution was found by removing three of the seven longitudinal rows of fine bubble diffusers in the CAPTOR aeration basins. This was done to create a spiral roll in the tanks, which leads to areas of rising and falling liquid with quite large channels down where the pads can fall. The spiral roll modification provided the necessary falling zone and produced complete mixing of the CAPTOR pads.

Another problem that occurred was maldistribution of the pads. The flow of wastewater tended to push the CAPTOR pads to the outlet of their zones, resulting in a concentration of 50–60 pads/L at the outlet and only 10–20 pads/L at the inlet end.

One other disturbing feature was the rapid deterioration in the CAPTOR pads. The CAPTOR pads used initially were black and were wearing at such a rate that they would not have lasted for more than 3 years, rendering the process uneconomical.

It had also become evident by this time that with the Freehold wastewater it would be possible to achieve the concentration of 200 mg biomass/pad predicted in the design. However, it was found that if the biomass was allowed to grow beyond 180 mg/pad, the biomass in the center of the pad became anaerobic. The control of pad biomass was difficult because the pad cleaners provided were not reliable and were situated at the CAPTOR zone inlets while most of the pads gravitated to the outlet ends of the zones.

During this early period, while the above problems were being tackled on the full-scale plant, there were some occasions when the effluent from the CAPTOR units was reasonable (BOD removals of 40–50%), but BOD removal never approached the average of 75% predicted based on the earlier pilot-plant results. Poor BOD removals were being experienced because the suspended solids concentration in the effluent was always high (>80 mg/L).

Consequently, more pilot-scale studies were used to find solutions to the operating problems described above before attempting further full-scale evaluation at Freehold.

5.2.5.2 Pilot-Scale Studies for Project Development

It was decided to evaluate two variations of the CAPTOR process. The new variation differed from the original CAPTOR in that the pads were placed directly into the mixed liquor of the activated sludge aeration tank rather than in a separate stage before the activated sludge tank. WRC named this process variation CAST (CAPTOR in activated sludge treatment). The CAST system had been applied to upgrade several overloaded wastewater treatment plants in Germany and France and was found to be useful in improving the treatment efficiency and plants' performance [60–62].

In addition, a single aeration tank filled with 40 CAPTOR pads/L was fed effluent from the above activated sludge control unit to assess the potential of CAPTOR as a second-stage nitrification process. Neither pad cleaning nor final clarification was necessary with this process variation because of the low sludge yields characteristic of nitrifier growth.

Studies were conducted using two well-mixed CAPTOR tanks in series. A range of loading and pad cleaning rates were used to evaluate process removal capabilities for CAPTOR. The intermediate effluent was used as a measure of process efficiency of the primary reactor and the final effluent for the entire system. This permitted plotting (Fig. 5.3) of % BOD_5 removal (total and soluble) vs. volumetric organic loading rate over the range of 1–3.5 kg BOD_5/day/m^3 (62–218 lb/day/1000 ft^3). High and low pad cleaning rates are differentiated in Fig. 5.4 as ≥16% and <16% of the total pad inventory/d, respectively [56].

Total BOD_5 removal efficiency was less than soluble BOD_5 removal efficiency because of the oxygen demand exerted by the biomass solids lost in the process effluent. The higher pad cleaning rates are believed to have contributed to the improved total and soluble BOD removals shown in Fig. 5.4, although low bulk liquid DOs may have adversely affected removals on some of the low cleaning runs. Low cleaning rates (<16%/day) were detrimental to soluble BOD_5 removal efficiency because of a gradual decline in activity of the biomass remaining in the pad.

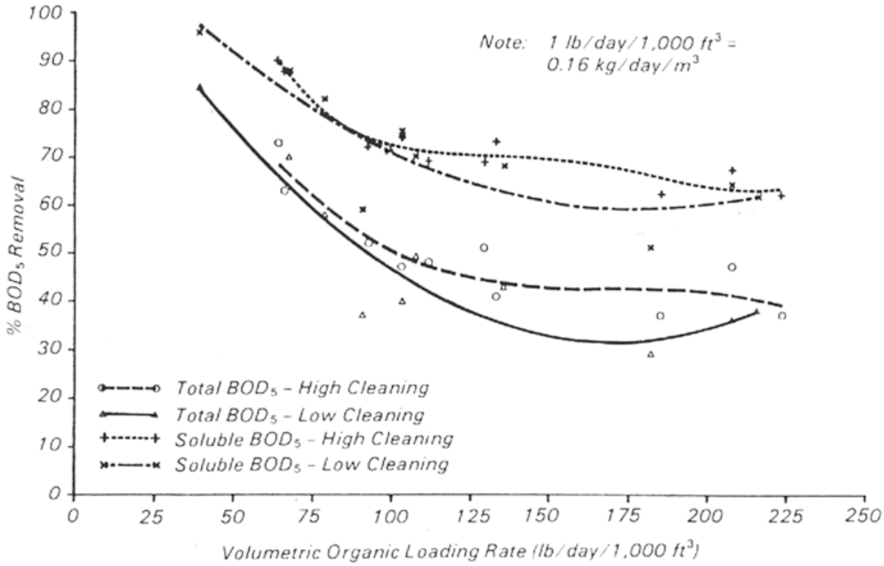

Fig. 5.4 Pilot-scale CAPTOR BOD_5 removals as a function of organic loading rate [56]

Cleaning rates greater than 24%/day, however, resulted in reduced biomass levels in the pads and a reduction in performance.

The problem of maldistribution of CAPTOR pads in the aeration tank (i.e., crowding of pads into the effluent end of the tank when operated in plug flow fashion as at Freehold) was solved by modifying the flow pattern to transverse flow (across the width of the tank rather than down the length). When implemented later at Freehold, this pattern resulted in a fourfold decrease in flow velocity.

Several mixing intensities and diffuser arrangements were tried to decrease biomass shedding into the process effluent. It became obvious, however, that production of effluent biomass solids was not significantly affected by changes in mixing intensity or diffuser arrangement. High effluent suspended solids proved to be far more dependent on pad cleaning rate, biochemical activity of the biomass, and biomass growth directly in the liquor.

Using the transverse flow scheme and a regular pad cleaning regimen, CAPTOR process performance was similar to that experienced in the small tanks. Operating parameters and process performance are summarized in Table 5.2 for two different volumetric loading rates [56].

Respiration studies conducted on pads indicated that biomass held within the pads respires at up to 40–50% less than equivalent biomass in free suspension. Any increase in net biomass concentration achieved in a CAPTOR reactor above that in a conventional activated sludge reactor may not produce noticeable benefits, therefore, due to the lower specific activity. These observations suggest that diffusion limitations were occurring in the CAPTOR pads.

The CAST variation of CAPTOR was operated in conjunction with a final clarifier to settle the mixed liquor solids component of the total biomass inventory and

Table 5.2 Pilot-scale operating conditions and process performance [56]

Parameter	Period 1		Period 2	
Volumetric loading (lb BOD_5/day/1000 ft^3)[a]	113		213	
HRT (h)	2.32		1.52	
Pads/L	40		40	
Biomass/pad (mg)	121		126	
Equivalent MLSS (mg/L)	4.840		5.040	
F/M loading (kg BOD_5/day/kgMLSS)	0.37		0.68	
SRT (days)	3.23		1.72	
DO (mg/L)	4.2		4.7	
	In	**Out**	**In**	**Out**
Total BOD_5 (mg/L)	175	93	216	129
Soluble BOD_5 (mg/L)	86	24	85	33
SS (mg/L)	116	120	178	160
Total BOD_5 removal (%)	47		40	
Soluble BOD_5 removal (%)	72		61	
SS removal (%)	−3		10	

[a] 1 lb/day/1000 ft^3 = 0016 kg/day/m^3

return it to the aeration tank. CAPTOR pads and biomass retained therein were kept in the reactor by screens. Operating and performance data are compared in Table 5.3 for the CAST unit and the parallel activated sludge control unit for a 25-day period when the volumetric loadings and hydraulic residence times (HRTs) for both units were identical.

In the nitrification experiments conducted on the CAPTOR process, the biomass concentrations per pad ranged from 99 to 124 mg. This is within the range of 100–150 mg/L reported by other researchers [63]. With a pad concentration of 40/L, equivalent MLSS levels varied from 3960 to 4960 mg/L. Liquor DO concentrations were maintained between 6.4 and 8.4 mg/L, and liquor temperature ranged from 11.50 to 6.5°C.

Secondary effluent from the control activated sludge pilot unit used in the CAST experiments was applied to the nitrification reactor over a range of loading conditions. Essentially complete nitrification was achieved at TKN and ammonia nitrogen loadings of approximately 0.25 kg/day/m^3 (15.6 lb/day/1000 ft^3) and 0.20 kg/day/m^3 (12.5 lb/day/1000 ft^3), respectively.

5.2.5.3 Full-Scale Plant Results After Modifications

Following the successful testing of the transverse mixing arrangement in the pilot-scale study, the two Freehold CAPTOR trains were modified. The modifications involved the following [56]:

Table 5.3 Pilot-scale CAST and activated sludge operating conditions and performance [56]

	System			
Parameter	CAST		Activated Sludge	
Volumetric loading (lb BOD_5/day/1.000 ft^3)[a]	148		148	
HRT (h)	1.8		1.8	
Pads/L	34		–	
Biomass/pad (mg)	116		–	
Equivalent MLSS in pads (mg/L)	3930		–	
MLSS in suspension (mg/L)	3720		6030	
Total MLSS (mg/L)	7650		6030	
F/M loading (kg BOD_5/day/kg total MLSS)	0.31		0.39	
SRT, based on total MLSS (days)	3.6		3.0	
DO (mg/L)	2.5		3.0	
	In	**Out**	**In**	**Out**
Total BOD_5 (mg/L)	178	12	178	20
Soluble BOD_5 (mg/L)	101	5	101	4
SS (mg/L)	121	15	121	23
Total BOD_5 removal (%)	93		89	
Soluble BOD_5 removal (%)	95		96	
SS removal (%)	88		81	

[a] 1 lb/day/1000 ft^3 = 0.016 kg/day/m^3

(a) Splitting each of the CAPTOR trains, C1 and C2, into two compartments, C1A and C1B and C2A and C2B, as shown in Fig. 5.5
(b) Feeding influent flow along long weirs at the side of the trains instead of at the narrow inlet ends
(c) Modifying the aeration pipework to place all three rows of dome diffusers directly below the outlet screens (covering about 25% of the width of the tanks), thereby creating a spiral roll of pads and liquid countercurrent to the flow of wastewater entering along the weirs on the sidewalls
(d) Installing two extra pad cleaners so that each CAPTOR subunit was provided with a cleaner
(e) Installing fine screens at the outlet from the primary clarifiers to reduce the quantity of floating plastic material entering the CAPTOR units that created problems with the cleaners

The objective of the first three modifications was to achieve uniform mixing of the pads in the CAPTOR units and prevent the situation that had occurred previously where high concentrations of pads (50–60 pads/L) collected at the outlet end and very low concentrations (10–20 pads/L) at the inlet end. Pads were removed from the tanks during the modifications. After the modifications were completed, the number of pads in each compartment was equalized at about 35/L.

The changes were completely successful in obtaining uniform distribution and complete mixing of the CAPTOR pads. A lithium chloride tracer test conducted on

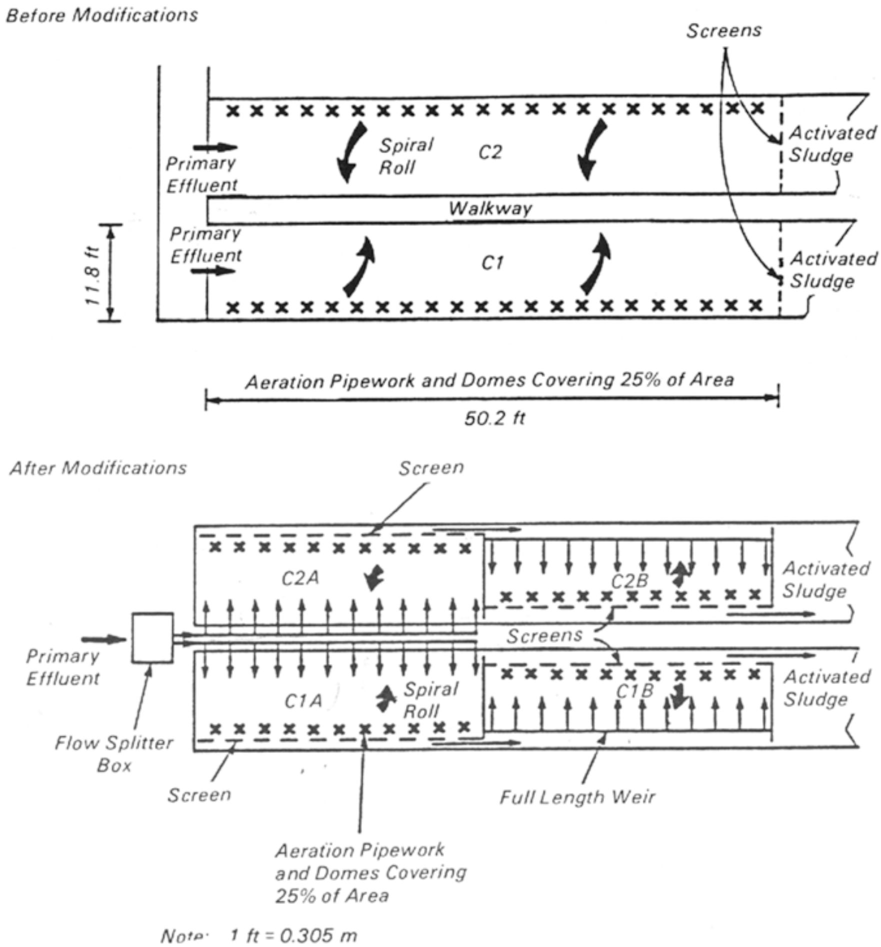

Fig. 5.5 Modifications to full-scale CAPTOR system flow pattern [56]

the modified tanks indicated that no dead zone was occurring in the "eye" of the roll. Formation of floating pad rafts (which had occurred at the outlet end of the tank with the original arrangement) was completely eliminated. The modifications, however, had no effect on the high level of suspended solids present in the liquor. The modified CAPTOR system was operated at an average volumetric loading rate of 1.24 kg BOD_5/day/m^3 (77 lb/day/1000 ft^3), an average HRT (excluding sludge recycle) of 2.55 h, and an overall biomass concentration of 4830 mg/L.

The CAST variation of the CAPTOR process, which had exhibited somewhat better performance than conventional activated sludge in the small tank experiments, was also field evaluated at Freehold. The CAPTOR trains were further modified so that return sludge could be introduced to the CAPTOR zones (35 pads/L), providing an activated sludge component throughout the entire aeration tanks, not just in the nitrification stage. The average volumetric organic loadings and HRTs (excluding sludge recycle) were 1.11 kg BOD_5/day/m^3 (69 lb/day/1000 ft^3) and 3.40 h, respectively.

Performance data summarized in Tables 5.4 and 5.5 indicate that the CAST system exhibits somewhat better performance than the CAPTOR version. In the CAST process, the removal of soluble BOD_5 is 96% compared to 90% in CAPTOR; the removal of total BOD_5 is 88% compared to 83%; and the removal of SS is about the same at about 78%.

5.2.5.4 Overall Conclusions

The US Environmental Protection Agency (USEPA) conclusions and recommendations for the CAPTOR/CAST treatment systems are as follows [55, 56, 64]:

(a) In the initial phase when the CAPTOR process was installed at the Freehold Sewage Treatment Works, several problems were immediately evident. There were major problems with respect to pad mixing, suspension, and distribution, and the process performance was adversely affected by the high level of suspended solids in the CAPTOR stage effluent. The problems of pad mixing and distribution were solved by pilot- and full-scale development work.
(b) The performance of the CAPTOR process was still adversely affected by the high level of suspended solids in the CAPTOR stage effluent after correction of the pad mixing, suspension, and distribution problems. This prevented the achievement of nitrification in the follow-on activated sludge stage.
(c) The presence of CAPTOR pads in the tank liquid did not improve oxygen transfer efficiency.
(d) The durability of the CAPTOR pads was solved by switching to different pads.
(e) The peak biomass concentration in the pads is unpredictable. It does not appear to be related to the BOD concentration of the wastewater. There were indications in the various studies, however, that the frequency of pad cleaning (and, hence, the biomass/pad concentration) was critical to the performance of the process. Regular pad cleaning is essential to prevent anaerobic conditions from developing in the pads.
(f) It is possible to raise the biomass concentration in a CAPTOR stage to 6000–8000 mg/L, but the respiration rate of the biomass in the pads is lower than the respiration of the same biomass if freely suspended and less than that of normal activated sludge. These data suggest that the geometry of the

Table 5.4 Full-scale modified CAPTOR performance results [56]

Parameter	Influent, mg/L	Effluent, mg/L	Removal, %
Total BOD_5	128	22	83
Soluble BOD_5	40	4	90
SS	138	32	77
NH_4-N	24	24.4	0

Table 5.5 Full-scale modified CAST performance results [56]

Parameter	Influent, mg/L	Effluent, mg/L	Removal, %
Total BOD_5	138	16	88
Soluble BOD_5	56	2	96
SS	120	27	78
NH_4-N	26.7	17.2	36

CAPTOR pads results in diffusion limitations, which demands further pad design improvement to enhance the potential for economic utilization of the CAPTOR process in wastewater treatment.

(g) The CAST variation of the CAPTOR process performs well.
(h) CAPTOR has the potential as an add-on package for tertiary nitrification.
(i) The CAPTOR option was projected to be more cost effective than extending the activated sludge plant for upgrading Freehold to complete year-round nitrification.
(j) For CAPTOR and CAST to achieve their full potential, as predicted by the pilot-scale studies, further design development and improvements are needed.

5.3 Activated Bio-filter (ABF)

5.3.1 Description

Activated bio-filters (ABF) are a recent innovation in the biological treatment field. This process consists of the series combination of an aerobic tower (bio-cell) with wood or other packing material, followed by an activated sludge aeration tank and secondary clarifier. Settled sludge from the clarifier is recycled to the top of the tower. In addition, the mixture of wastewater and recycle sludge passing through the tower is also recycled around the tower, in a similar manner to a high-rate trickling filter. No intermediate clarifier is utilized. Forward flow passes directly from the tower discharge to the aeration tank (Fig. 5.6). The use of the two forms of biological treatment combines the effects of both fixed and suspended growth processes in one system. The microorganisms formed in the fixed growth phase are passed along to the suspended growth unit, whereas the suspended growth microorganisms are recycled to the top of the fixed media unit [65]. This combination of the two processes results in the formation of a highly stable system that has excellent performance and good settling biological floc when treating wastewaters that have variable loads [66].

The bio-media in the bio-cell consists of individual racks made of wooden laths fixed to supporting rails. The wooden laths are placed in the horizontal direction, permitting wastewater to pass downward, and air horizontally and vertically. The horizontal surfaces reduce premature sloughing of biota. Droplet formation and

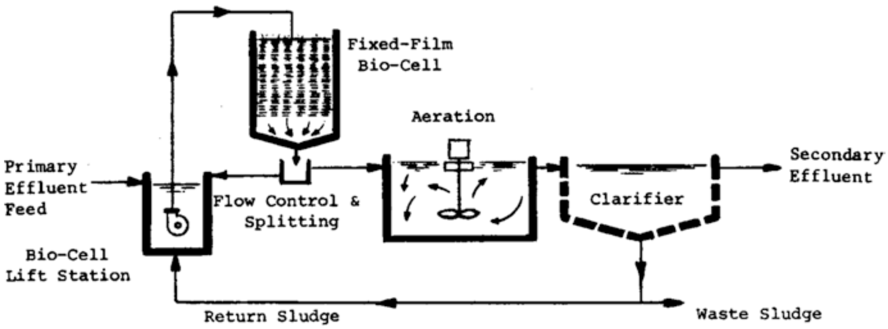

Fig. 5.6 ABF process flow diagram [65]

breakup induced by wastewater dripping from lath to lath enhances oxygen transfer. Other types of material for the bio-media have also been reported by other researchers and equipment manufacturers [67–70]. The aeration basin is a short detention unit that can be designed for either plug flow or complete mix operation. The effluent from the aeration basin passes to a secondary clarifier where the activated sludge is collected and recycled to the top of the bio-cell tower and to waste.

ABF units can be used for the removal of either carbonaceous material or for carbonaceous removal plus nitrification by appropriately modifying the detention time of the aeration basin. When nitrification is desired, the bio-cell acts as a first-stage roughing unit and the aeration basin as a second-stage nitrification unit [71, 72]. ABF bio-cells can be either rectangular or round. Various types of aeration equipment can be used in the aeration system, including both surface and diffused aerators. The detention time of the aeration tank can be modified, depending on influent quality and desired effluent quality. ABF units can be supplied with mixed media effluent filters for enhanced treatment.

5.3.2 Applications

Activated bio-filters can be used for treating municipal wastewater and biodegradable industrial wastewater. ABF systems are especially useful where [65, 66]:

(a) Both BOD_5 removal and nitrification are required.
(b) Land availability is low.
(c) Raw wastewater organic loadings fluctuate greatly, due to its ability to handle shock conditions.
(d) Existing trickling filter facilities and overloaded existing secondary plants need to be upgraded at reduced cost.

A typical ABF application is the Burwood Beach Wastewater Treatment Works in Australia [73]. The plant was upgraded in the 1990s using ABF at a cost of $48 M. The facility currently serves a population of 180,000 with a flow of 43 ML a day and has the capacity to treat 53 ML/day for a population of 220,000 in the year 2020. The bio-filter is 30 m in diameter and has a design organic loading of 3.2 kg BOD_5/m^3/day. The aeration tank is designed for 1.5 h of hydraulic detention time. The plant has been in operation for around 10 years producing an effluent that is consistently within the required USEPA set limits.

5.3.3 Design Criteria

The design criteria for the ABF system are reported to be as follows [65, 74, 75]:

(a) Bio-cell organic load: 100–200 lb BOD_5/day/1000 ft^3
(b) Return sludge rate: 25–100%
(c) Bio-cell recycle rate: 0–100%
(d) Bio-cell hydraulic load: 1–5.5 gpm/ft^2
(e) Aeration basin detention time: 0.5–3.0 h for BOD_5 removal only
5.8–7.5 h for two-stage nitrification
(f) System F/M: 0.25–1.5 lb BOD_5/day/lb MLVSS for BOD removal
0.18 lb BOD_5/day/lb MLVSS for two-stage nitrification.

5.3.4 Performance

ABF systems are quite stable and highly reliable. They can treat standard municipal, combined municipal/industrial, or industrial wastewaters to BOD_5 and suspended solids levels of 20 mg/L or less. Test study on a package system showed at least 90% removal of BOD_5, TSS, and NH_4-N [65]. The detailed results are shown in Table 5.6.

Sludge production was reported at 0.25–1.0 lb of waste VSS per lb of BOD_5 removed. The mean yield over the course of the study was 0.60 lb VSS per lb of BOD removed.

Table 5.6 Performance of BAF systems [65]

Parameter	Influent, mg/L	Effluent, mg/L	Removal, %
BOD_5	153	14	91
COD	330	58	82
TSS	222	20	91
NH_4-N[a]	20	1	90

[a] When used for nitrification

5.4 Vertical Loop Reactor (VLR)

5.4.1 Description

A Vertical Loop Reactor (VLR) is an activated sludge biological treatment process similar to an oxidation ditch [76, 77]. 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, as shown in Fig. 5.7 [78]. A typical VLR consists of an 18 ft deep concrete or steel basin with a horizontal baffle extending the entire width of the reactor and most of its length. Operating basins are reported to have sidewall depths which range from approximately 10–22 ft [79]. 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 baffle is generally 5–11 ft below the surface of the water. 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 at a velocity of 1–1.5 ft/s [80]. 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. This extended bubble contact time increases the process aeration efficiency. Denitrification in an anoxic zone also reduces oxygen requirements.

The VLR process is usually preceded by preliminary treatment such as screening, comminution, or grit removal. Secondary settling of the VLR effluent is typically provided by a separate clarifier. An intra-channel 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 10–15 h.

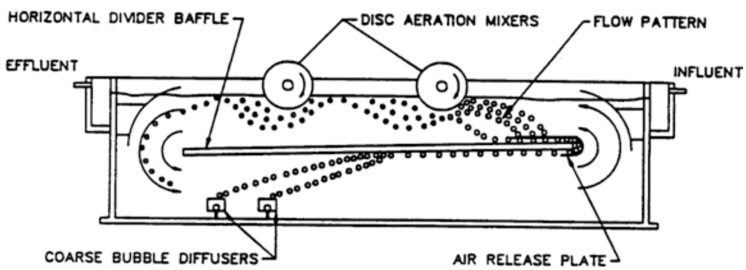

Fig. 5.7 Diagram of the Vertical Loop Reactor [77, 78]

5.4.2 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. There are currently more than ten municipal wastewater treatment facilities in the United States with VLRs. One such example is the City of Willard, OH, United States, wastewater treatment plant [81]. The facility is designed for an average daily flow of 4.5 MGD and is capable of handling a peak flow of 7.2 MGD.

The following advantages have been reported for VLR systems [82]:

(a) The land area required for VLRs is about 40% less than for oxidation ditches.
(b) The VLR aeration basin cost is about 30% less than for oxidation ditches.
(c) The multiple tank basin series arrangement is an advantage for facilities with highly variable flow.
(d) VLRs are useful for retrofitting existing basins for plant upgrade to suit increased flows or more stringent effluent requirements.

5.4.3 Design Criteria

The design criteria for the VLR process are reported to be as follows [76]:

BOD loading: 14–22 lb BOD_5/1000 ft^3/day
SRT: 17–36 day
Detention Time: 12–24 h

5.4.4 Performance

The average effluent BOD_5 and TSS concentrations for the five studied operating VLR facilities are 4.2 and 7.1 mg/L, respectively. The average effluent ammonia concentration is 0.8 mg/L. 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.

The VLR system is quite reliable. Table 5.7 indicates the percent of time the monthly average effluent concentration of the given pollutants was less than the

Table 5.7 Reliability of the VLR treatment process [76]

Concentration, mg/L	BOD[a]	NH_3-N[a]	TSS[a]	P[a]
0.2	0	30	0	2
0.5	0	63	1	10
1.0	0	83	1	24
2.0	20	88	5	63
3.0	71	95	43	93
10.0	97	96	75	100
20.0	100	100	96	100
Number of plants	5	5	5	1

[a] Percentage of time the monthly average concentration of the pollutant was less than the stated value in the first column

concentration given in the first column. No significant difference in results was observed between winter and summer data.

5.4.5 USEPA Evaluation of VLR

The following summarizes the major findings and conclusions of USEPA evaluation of VLRs [77]. The information is based on analysis of available information from site visits, a detailed design of a full-scale VLR system, and information from consultants and manufacturers.

(a) 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, 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 bypass design for treatment of high peak to average flows.
(b) There are currently over ten operating VLRs in the United States ranging in size from 0.22 to 5.0 MGD.
(c) Performance data from operating VLRs show that this process is capable of achieving effluent carbonaceous biochemical oxygen demand levels of less than 10 mg/L, effluent total suspended solids 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 60–80%.
(d) The VLR process is applicable for flows ranging from 0.05 to over 10 MGD.
(e) The claimed advantages of this process by the manufacturer include the following:

- Higher dissolved oxygen transfer than conventional equivalent technology
- Improved response to peak flows due to a stormwater bypass feature

- A credit for oxygen release due to denitrification with the credit based on 80% denitrification
- Increased mixed liquor settleability and process stability

(f) The design criteria for the existing VLRs are conservative. HRTs range from 11.9 to 24 h. Volumetric loading ranged from 13.6 to 23.1 lbs CBOD/1000 ft^3. 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.

(g) The VLR technology has been designated as Innovative Technology by the EPA for three plants due to a 20% claimed energy savings.

(h) Based on this assessment, the 20% energy savings over competing technology could not be verified.

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

- The VLR technology produces comparable to slightly improved effluent levels of BOD, TSS, and NH_3-N than oxidation ditch plants.
- Total removal of phosphorus and total nitrogen are equivalent to oxidation ditches designed for the same level of treatment.
- The energy requirements for aeration were found to be similar to 10% less than for oxidation ditches.
- The land area required for VLRs was found to be approximately 40% less than for oxidation ditches based on equivalent aeration tank loadings.
- The VLR aeration basin cost was found to be approximately 30% less than for oxidation ditches for situations where rock excavation is not required for the deeper VLR basin.
- A definitive comparison of total VLR plant costs to total oxidation plant costs could not be made. Data submitted from both manufacturers indicated a comparable cost for plants in the 0–2 MGD range. The reported VLR costs 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.
- The total operation and maintenance costs of the two technologies were found to be similar.

5.4.6 Energy Requirements

The VLR energy requirements are shown in Fig. 5.8. The requirements are based on the following assumptions [76]:

(a) Water quality

    BOD_5: influent = 200 mg/L, effluent = 20 mg/L

    TKN: influent = 35 mg/L, effluent = 1 mg/L

(b) Design basis

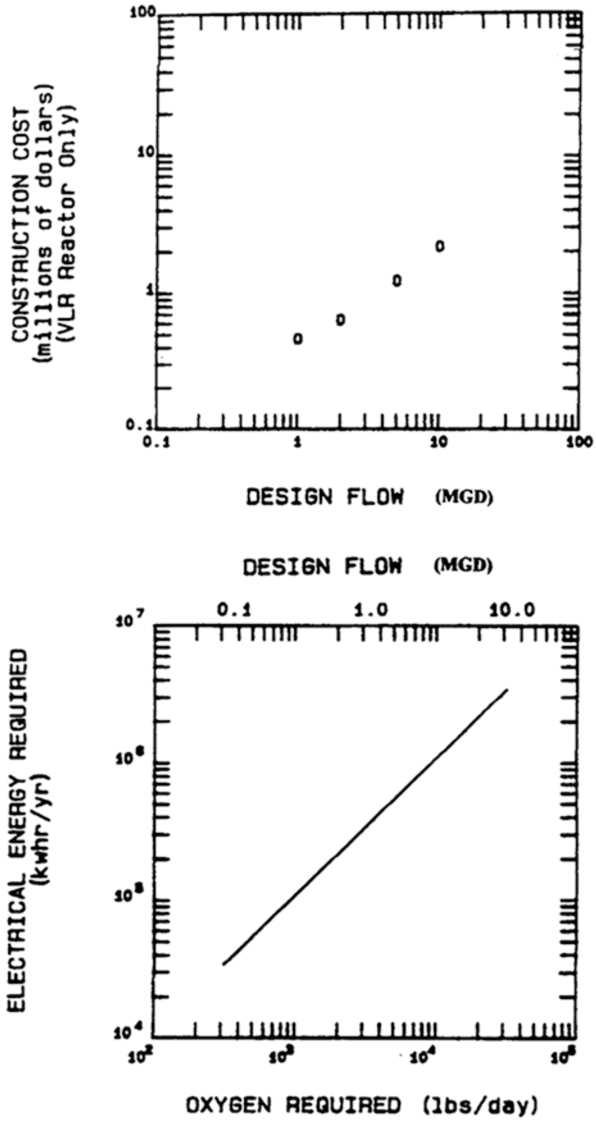

Fig. 5.8 VLR energy requirements and construction cost [76, 77]

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

(c) Operating parameters
Oxygen requirement: 1.5 lb O_2/lb BOD_5 removed
4.57 lb O_2/lb TKN removed

(d) Type of energy: electrical

5.4.7 Costs

The construction costs (1991 Dollars, Utilities Index = 392.35) for VLR are shown in Fig. 5.8. To obtain the values in terms of the present 2004 US Dollars, using the Cost Index for Utilities (Appendix 1), multiply the costs by a factor of 506.13/392.35 = 1.29 [83]. The operation costs are similar to oxidation ditch type treatment plant.

5.5 PhoStrip Process

5.5.1 Description

"PhoStrip" is a combined biological-chemical precipitation process based on the use of activated sludge microorganisms to transfer phosphorus from incoming wastewater to a small concentrated substream for precipitation. As illustrated in Fig. 5.9, the activated sludge is subjected to anoxic conditions to induce phosphorus release into the substream and to provide phosphorus uptake capacity when the sludge is returned to the aeration tank. Settled wastewater is mixed with return activated sludge in the aeration tank. Under aeration, sludge microorganisms can be induced to take up dissolved phosphorus in excess of the amount required for growth. The mixed liquor then flows to the secondary clarifier where liquid effluent, now largely free of phosphorus, is separated from the sludge and discharged. A portion of the phosphorus-rich sludge is transferred from the bottom of the clarifier to a thickener-type holding tank: the phosphate stripper. The settling sludge quickly becomes anoxic and, thereupon, the organisms surrender phosphorus, which is mixed into the supernatant. The phosphorus-rich supernatant, a low-volume, high-concentration substream, is removed from the stripper and treated with lime for phosphorus precipitation. The thickened sludge, now depleted in phosphorus, is returned to the aeration tank for a new cycle [65]. The readers are referred to the

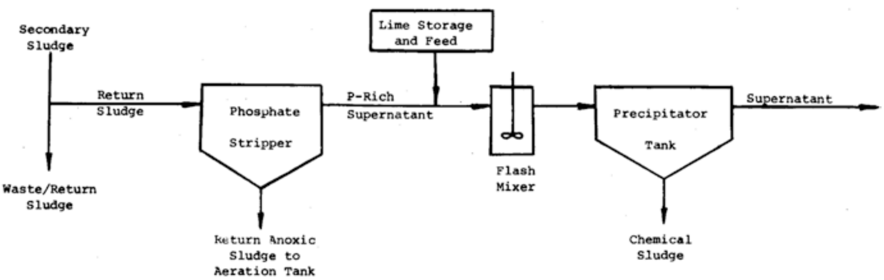

Fig. 5.9 PhoStrip process flow diagram [65]

literature [84–97] for additional innovative wastewater and sludge treatment processes, such as biological sequencing batch reactor, physicochemical sequencing batch reactor, membrane bioreactor, flotation bioreactor, membrane flotation bioreactor, Symbio process, column bioreactor clarifier process, upflow sludge blanket filtration, deep well injection, land application, aerobic granulation technology, vertical shaft bioreactor, vertical shaft digestion, bioreactor landfill, post aeration, etc.

The PhoStrip process has demonstrated a compatibility with the conventional activated sludge process and is compatible with its modifications. The process can operate in various flow schemes, including full or split flow of return activated sludge through the phosphate stripper, use of an elutriate to aid in the release of phosphorus from the anoxic zone of the stripper, or returning lime-treated stripper supernatant to the primary clarifier for removal of chemical sludge.

This technique is a new development in municipal wastewater treatment and has been demonstrated in pilot-plant and full-scale studies. Notable large-scale evaluations have been conducted at Seneca Falls, New York, United States, and, more recently, Reno/Sparks, Nevada, United States. Nearly a dozen commercial installations are reported to be in the operational phase.

5.5.2 Applications

This method, which involves a modification of the activated sludge process, can be used in removing phosphorus from municipal wastewaters to comply with most effluent standards. Direct chemical treatment is simple and reliable, but it has the two disadvantages of significant sludge production and high operating costs. The PhoStrip system reduces the volume of the substream to be treated, thereby reducing the chemical dosage required, the amount of chemical sludge produced, and associated costs. Lime is used to remove phosphorus from the stripper supernatant at lower pH levels (8.5–9.0) than normally required. The cycling of sludge through an anoxic phase may also assist in the control of bulking by the destruction of filamentous organisms to which bulking is generally attributed [65].

On the negative side, it should be pointed out that more equipment and automation, along with a greater capital investment, are normally required than for conventional chemical addition systems. Since this method relies on activated sludge microorganisms for phosphorus removal, any biological upset that hinders uptake ability will also affect effluent concentrations. It has been found that sludge in the stripper tank is very sensitive to the presence of oxygen. Anoxic conditions must be maintained for phosphorus release to occur.

Table 5.8 Typical design criteria for the PhoStrip process [74]

Design parameter	Unit	Value
Food-to-microorganism ratio (F/M)	lb BOD/lb MLSS/day	0.1–0.5
Solids retention time (SRT)	day	10–30
Mixed liquor suspended solids (MLSS)	mg/L	600–5000
Hydraulic retention time in stripper (t)	h	8–12
Hydraulic retention time in aeration tank (t)	h	4–10
Return activated sludge (RAS)	% of influent	20–50
Internal recycle (stripper underflow)	% of influent	10–20

5.5.3 Design Criteria

The fraction of the total sludge flow which must be processed through the stripper tank is determined by the phosphorus concentration in the influent wastewater to the treatment plant and the level required in the treated effluent. The required detention time in the stripper tank ranges from 5 to 15 h. Typical phosphorus concentrations produced in the stripper are in the range of 40–70 mg/L. The volume of the phosphorus-rich supernatant stream to be lime treated is 10–20% of the total flow [65]. Typical design criteria for the PhoStrip process are shown in Table 5.8 [74].

5.5.4 Performance

Pilot- and full-scale studies of the process have shown it to be capable of reducing the total phosphorus concentration of typical municipal wastewaters to 1.5 mg/L [74] or even to 0.5 mg/L or less [75]. A plant-scale evaluation of the method treating 6 MGD of municipal wastewater at the Reno/Sparks Joint Water Pollution Control Plant in Nevada demonstrated satisfactory performance for achieving greater than 90% phosphorus removal. Results showed that the process enhanced the overall operation and performance of the activated sludge process, since it produced a more stable, better settling sludge. Regular maintenance of mechanical equipment, including pumps and mixers, is necessary to ensure proper functioning of the entire system.

5.5.5 Cost

5.5.5.1 Construction Cost

The construction costs (1980 Dollars, Utilities Index = 277.60) for PhoStrip are shown in Fig. 5.10. To obtain the values in terms of the present 2004 US Dollars, using the Cost Index for Utilities (Appendix 1), multiply the costs by a factor of

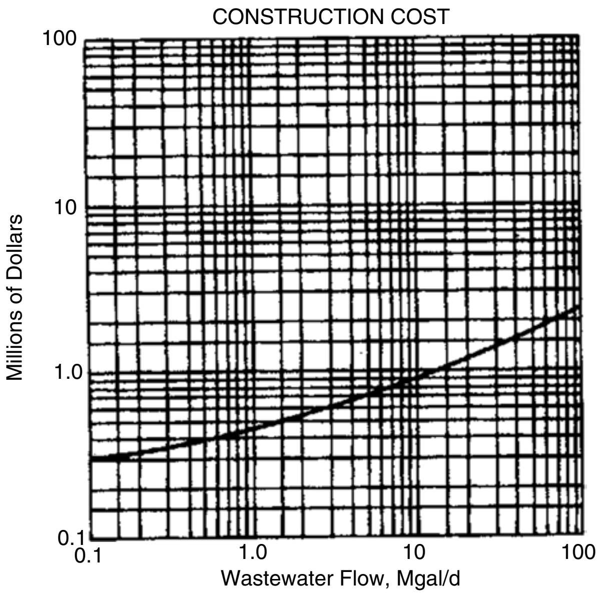

Fig. 5.10 PhoStrip construction cost [65]

506.13/277.60 = 1.82 [83]. Construction costs include stripper (10 h detention time at 50% of return sludge), flash mixer, flocculator/clarifier, thickeners, and lime feed and storage facilities [65].

5.5.5.2 Operation and Maintenance Cost

The electrical energy required for operation of pumps, lime mixing equipment, and clarifiers is shown in Fig. 5.11. The operation and maintenance costs (1980 Dollars, Utilities Index = 277.60) for PhoStrip are shown in Fig. 5.12. To obtain the values in terms of the present 2004 US Dollars, using the Cost Index for Utilities (Appendix 1), multiply the costs by a factor of 506.13/277.60 = 1.82 [83]. Operation and maintenance costs include labor for operation, preventive maintenance, and minor repairs; materials to include replacement parts and major repair work; and lime and power cost based on the electrical energy requirement shown in Fig. 5.11 [65].

Glossary

Activated bio-filter (ABF) Activated bio-filters are a recent innovation in the biological treatment field. This process consists of the series combination of an aerobic tower (bio-cell) with wood or other packing material, followed by an

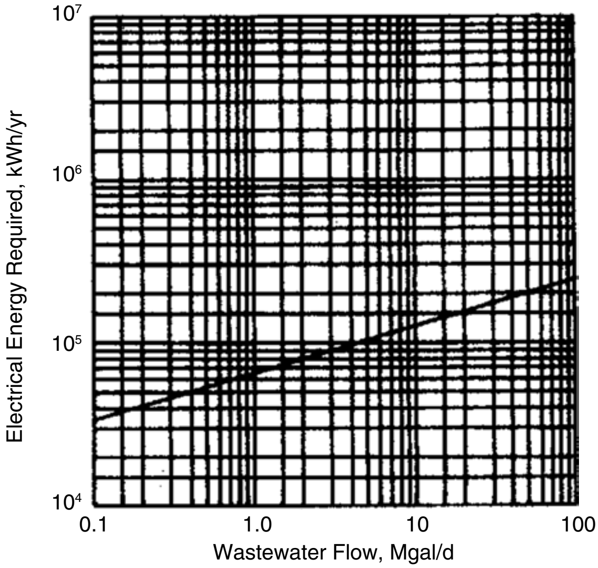

Fig. 5.11 PhoStrip electrical energy requirement [65]

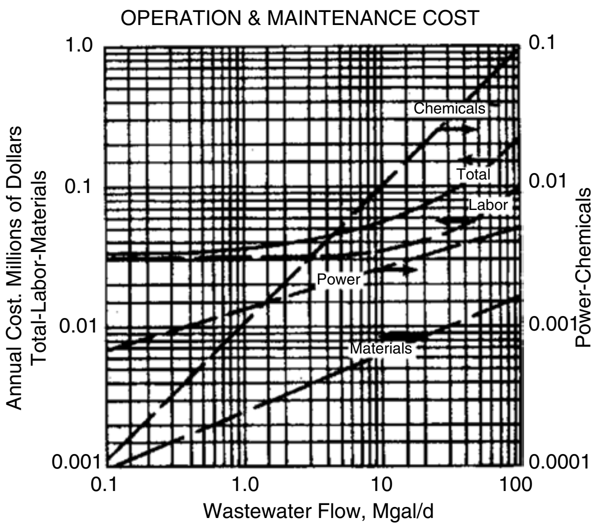

Fig. 5.12 PhoStrip operation and maintenance cost [65]

activated sludge aeration tank and secondary clarifier. Settled sludge from the clarifier is recycled to the top of the tower. In addition, the mixture of wastewater and recycle sludge passing through the tower is also recycled around the tower, in a similar manner to a high-rate trickling filter. No intermediate clarifier is utilized. Forward flow passes directly from the tower discharge to the aeration tank. The use of the two forms of biological treatment combines the effects of both fixed and suspended growth processes in one system. The microorganisms formed in the fixed growth phase are passed along to the suspended growth unit, whereas the suspended growth microorganisms are recycled to the top of the fixed media unit. This combination of the two processes results in the formation of a highly stable system that has excellent performance and good settling biological floc when treating wastewaters that have variable loads.

Carrier-activated sludge processes (CAPTOR and CAST systems) There has been a substantial interest in recent years in the potential benefits of high biomass wastewater treatment. The major obstacle for achieving this has been the inability of biosolids separation in secondary clarifiers. For the most part, this has been overcome by using various forms of support media or carriers that have the ability to attach high concentrations of aerobic bacterial growth. The increase in immobilized biomass reduces the process dependence on secondary settling basins for clarification. In such hybrid systems where attached growth coexists with suspended growth, one gets more stable systems which possess the combined advantages of both fixed and suspended growth reactors.

PACT activated sludge process The powdered activated carbon (PAC) activated sludge system is a process modification of the activated sludge process. PAC is added to the aeration tank where it is mixed with the biological solids. The mixed liquor solids are settled and separated from the treated effluent. In a gravity clarifier, polyelectrolyte will normally be added prior to the clarification step to enhance solids-liquid separation. If phosphorus removal is necessary, alum is often added at this point also. Even with polyelectrolyte addition, tertiary filtration is normally required to reduce the level of effluent suspended solids. The clarifier underflow solids are continuously returned to the aeration tank. A portion of the carbon-biomass mixture is wasted periodically to maintain the desired solids inventory in the system.

PhoStrip process "PhoStrip" is a combined biological-chemical precipitation process based on the use of activated sludge microorganisms to transfer phosphorus from incoming wastewater to a small concentrated substream for precipitation. The activated sludge is subjected to anoxic conditions to induce phosphorus release into the substream and to provide phosphorus uptake capacity when the sludge is returned to the aeration tank. Settled wastewater is mixed with return activated sludge in the aeration tank. Under aeration, sludge microorganisms can be induced to take up dissolved phosphorus in excess of the amount required for growth. The mixed liquor then flows to the secondary clarifier where liquid effluent, now largely free of phosphorus, is separated from the sludge and discharged. A portion of the phosphorus-rich sludge is transferred from the bottom of the clarifier to a thickener-type holding tank: the phosphate stripper. The settling sludge quickly becomes anoxic and, thereupon, the organisms surrender phosphorus, which is mixed into the supernatant. The phosphorus-rich supernatant, a low-volume, high-concentration substream, is removed from the stripper and treated with lime for phosphorus precipitation. The thickened sludge, now depleted in phosphorus, is returned to the aeration tank for a new cycle.

Vertical Loop Reactor (VLR) A Vertical Loop Reactor (VLR) is an 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 ft deep concrete or steel basin with a horizontal baffle extending the entire width of the reactor and most of its length. Operating basins are reported to have sidewall depths which range from approximately 10–22 ft. 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 baffle is generally 5–11 ft below the surface of the water. Because a VLR is typically deeper than an oxidation ditch, the VLR requires less land area.

Appendix 1: US Yearly Average Cost Index for Utilities [83]

Year	Index	Year	Index
1967	100	1995	439.72
1968	104.83	1996	445.58
1969	112.17	1997	454.99
1970	119.75	1998	459.40
1971	131.73	1999	460.16
1972	141.94	2000	468.05
1973	149.36	2001	472.18
1974	170.45	2002	486.16
1975	190.49	2003	497.40
1976	202.61	2004	563.78
1977	215.84	2005	605.47
1978	235.78	2006	645.52
1979	257.20	2007	681.88
1980	277.60	2008	741.36
1981	302.25	2009	699.70
1982	320.13	2010	720.80
1983	330.82	2011	758.79
1984	341.06	2012	769.30
1985	346.12	2013	776.44
1986	347.33	2014	791.59
1987	353.35	2015	786.32
1988	369.45	2016	782.46
1989	383.14	2017	803.93

(continued)

Year	Index	Year	Index
1990	386.75	2018	841.84
1991	392.35	2019	866.18
1992	399.07	2020	867.71
1993	410.63	2021	893.02[a]
1994	424.91	2022	918.91[a]

[a]Projected future cost index values

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