14
Aerobic and Anaerobic Attached Growth Biotechnologies

Nazih K. Shammas and Lawrence K. Wang

CONTENTS

Abstract Among the attached growth biological treatment processes covered in this chapter are trickling filter, denitrification filter, rotating biological contactor (RBC), fluidized bed reactor (FBR), packed bed reactor (PBR), biological aerated filter (BAF), and hybrid biological-activated carbon systems including downflow conventional biological GAC systems and upflow fluidized bed biological GAC systems (FBB-GAC). This chapter describes the above processes and explains their practice, limitations, process design, performance, energy requirements, process equipment, costs, and case studies.

Key Words Attached growth • trickling filter • denitrification filter • rotating biological contactor • biocontactor • fluidized bed reactor • packed bed reactor • biological aerated filter • hybrid systems • downflow conventional biological GAC systems; upflow fluidized bed biological GAC system.

1. TRICKLING FILTER

The trickling filter consists of a fixed bed of rock or plastic media over which wastewater is applied for aerobic biological treatment. Zoogleal slimes form on the media, which assimilate

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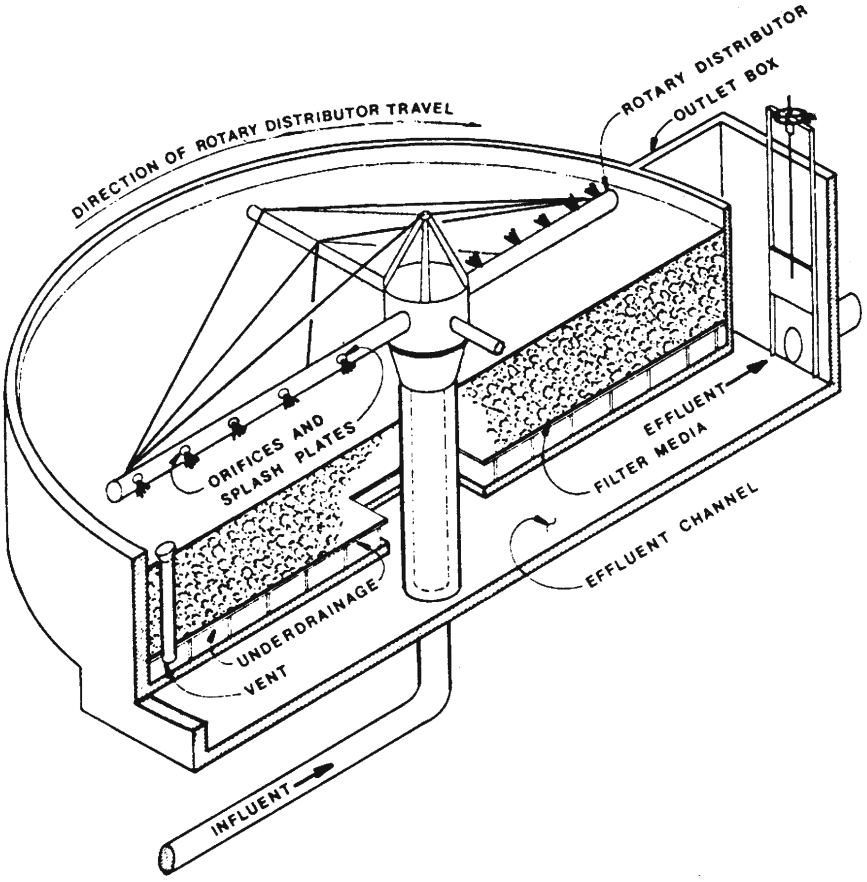

Fig. 14.1. Trickling filter with rotary distribution system (U.S. EPA).

and oxidize substances in the wastewater. The bed is dosed by a distributor system, and the treated wastewater is collected by an underdrain system. Primary treatment is normally required to optimize trickling filter performance.

Containment structures are normally made of reinforced concrete and installed in the ground to support the weight of the media. The rotary distributor has become the standard because of its reliability and ease of maintenance (Fig. 14.1). It consists of two or more arms that are mounted on a pivot in the center of the filter. Nozzles distribute the wastewater as the arms rotate as a result of the dynamic action of the incoming primary effluent. Underdrains are manufactured from specially designed vitrifiedclay blocks that support the filter media and pass the treated wastewater to a collection sump for transfer to the final clarifier (1, 2).

The organic material present in the wastewater is degraded by a population of microorganisms attached to the filter media. As the microorganisms grow, the thickness of the slime layer increases. Periodically, wastewater washes the slime off the media, and a new slime layer

starts to grow. This phenomenon of losing the slime layer is called sloughing and is primarily a function of the organic and hydraulic loadings on the filter.

Some advantages and disadvantages of trickling filters are listed below (3, 4).

(a) Advantages:
1. Simple, reliable, biological process.
2. Suitable in areas where large tracts of land are not available for land-intensive treatment systems.
3. May qualify for equivalent secondary discharge standards.
4. Effective in treating high concentrations of organics depending on the type of medium used.
5. Appropriate for small and medium-sized communities.
6. Rapidly reduce soluble BOD_5 in applied wastewater.
7. Efficient nitrification units.
8. Durable process elements.
9. Low power requirements.
10. Moderate level of skill and technical expertise needed to manage and operate the system.

(b) Disadvantages
1. Additional treatment may be needed to meet more stringent discharge standards.
2. Possible accumulation of excess biomass that cannot retain an aerobic condition and can impair performance (maximum biomass thickness is controlled by hydraulic dosage rate, type of media, type of organic matter, temperature, and nature of the biological growth).
3. Requires regular operator attention.
4. Incidence of clogging is relatively high.
5. Requires low loadings depending on the medium.
6. Flexibility and control are limited in comparison with activated sludge processes.
7. Vector and odor problems.
8. Snail problems.

1.1. Low-Rate Trickling Filter, Rock Media

The filter media for the low-rate trickling filter consists of 1- to 5-in (2.54 to 12.7 cm) stone. In contrast to the high-rate trickling filter that uses continuous recirculation of filter effluent to maintain a constant hydraulic loading to the distributor arms, either a suction-level controlled pump or a dosing siphon is employed for that purpose with a low-rate filter. Nevertheless, programmed rest periods may be necessary at times because of inadequate influent flow.

The low-rate trickling filter media bed is generally circular in plan, with a depth of 5–10 ft (1.52–3.04 m). Although filter effluent recirculation is generally not utilized, it can be provided as a standby tool to keep filter media wet during low flow periods (5).

The process is widely used and is highly dependable in moderate climates. Use of after-treatment or multistaging has frequently been found necessary to ensure uniform compliance with effluent limitations in colder regions. The trend in new installations is to replace the rock media with plastic media systems.

1.1.1. Applications

Slow trickling filters are used for the treatment of domestic and compatible industrial wastewaters amenable to aerobic biological treatment in conjunction with suitable pretreatment. This process is good for removal of suspended or colloidal materials and is somewhat

less effective in removal of soluble organics. This type of filter can be used for nitrification following prior (first-stage) biological treatment or as a stand-alone process in warm climates if the organic loading is low enough.

1.1.2. Limitations

- Slow rate trickling filters are vulnerable to climate changes and low temperatures.
- Filter flies and odors are common.
- Periods of inadequate moisture for slimes can be common.
- Less effective in treatment of wastewater containing high concentrations of soluble organics.
- Limited flexibility and process control in comparison with competing processes.
- High land and capital cost requirements, and
- Recovery times of several weeks with upsets.

1.1.3. Performance

Single-stage configuration with primary and secondary clarification and no recirculation are expected to have the following percent removals:

- 5-day Biochemical Oxygen Demand (BOD_5): 75–90%
- Phosphorus: 10–30%
- NH_4-N: 20–40%
- Suspended Solids (SS): 75–90%

Generated residual of biosolids is withdrawn from the secondary clarifier at a rate of 3,000–4,000 gal/MG (4,000 L/ML) of wastewater, containing 500–700 lb (226.8–317.5 kg) dry solids.

1.1.4. Design Criteria

Design criteria for low-rate trickling filters include the following (1, 3, 4):

- Hydraulic loading: 1–4 MG/acre/d (25–90 $gal/d/ft^2$) = 1.02–3.67 $m^3/d/m^2$
- Organic loading: 200–900 lb $BOD_5/d/acre\,ft$ (5–20 lb $BOD_5/d/1,000\,ft^3$) = 80–320 $g/d/m^3$
- Dosing interval: Continuous for majority of daily operating schedule, but may become intermittent (not more than 5 min) during low flow periods
- Effluent channel minimum velocity: 2 ft/s at average daily flow
- Media: Rock, 1–5 in (2.54–12.7 cm), must meet sodium sulfate soundness test
- Recirculation ratio: 0
- Depth: 5–10 ft, or 1.52–3.04 m
- Sloughing: Intermittent
- Underdrain minimum slope = 1%

1.2. High-Rate Trickling Filter, Rock Media

The high-rate filter media consists of 1- to 5-in (2.54 to 12.7 cm) stone similar to slow-rate filters. Continuous recirculation of filter effluent is used to maintain a constant hydraulic loading to the distributor arms. The high-rate trickling filter media bed is generally circular in plan, with a depth of 3–6 ft (0.91–1.82 m) (1–4).

The organic material present in the wastewater is degraded by a population of microorganisms attached to the filter media. As the slime layer increases in thickness, the absorbed organic matter is metabolized before it can reach the microorganisms near the media face. As

a result, the microorganisms near the media face enter into an endogenous phase of growth. In this phase, the microorganisms lose their ability to cling to the media surface. The liquid then washes the slime off the media, and a new slime layer starts to grow. Filters effluent recirculation is vital with high-rate trickling filters to promote the flushing action necessary for effective sloughing control, without which media clogging and anaerobic conditions could develop because of the high organic leading rates employed.

1.2.1. Applications

High-rate trickling filters are used in the treatment of domestic and compatible industrial wastewaters amenable to aerobic biological treatment in conjunction with suitable pre- and posttreatment. Industrial and joint wastewater treatment facilities may use the process as a roughing filter prior to activated sludge or other unit processes. The process is effective for removal of suspended or colloidal materials and is less effective removal of soluble organics. When used for secondary treatment, the media bed is generally circular in plan and dosed by a rotary distributor (Fig. 14.1). Roughing applications often utilize rectangular media beds with fixed nozzles for distribution (Fig. 14.2).

1.2.2. Limitations

1. Vulnerable to below freezing weather
2. Recirculation may be restricted during cold weather due to cooling effects
3. Marginal treatment capability in single-stage operation

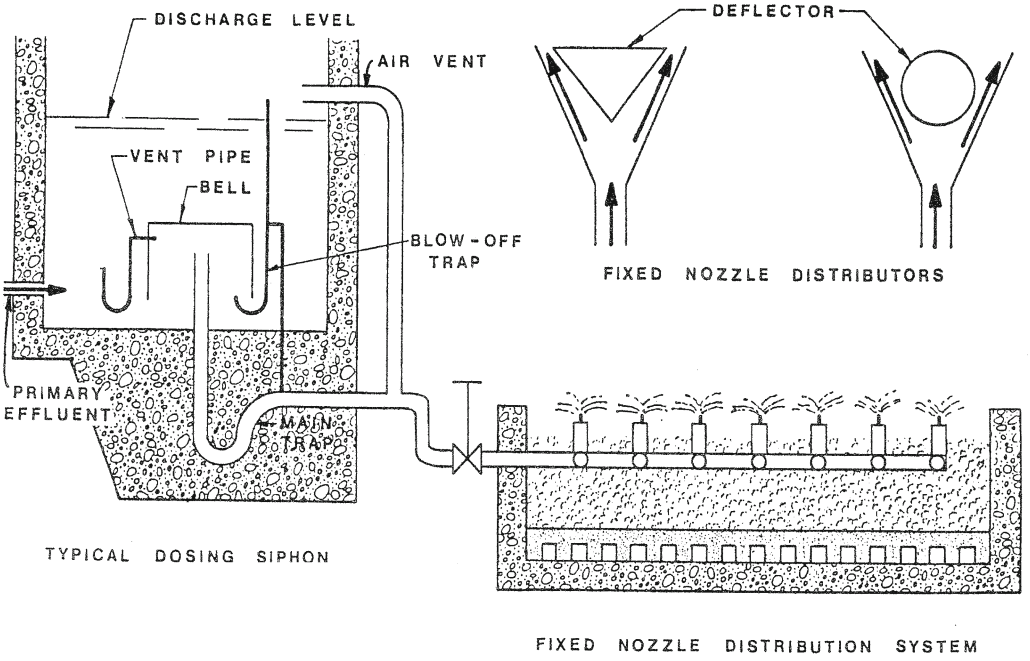

Fig. 14.2. Trickling filter with fixed nozzle distribution system (U.S. EPA).

4. Is less effective in treatment of wastewater containing high concentrations of soluble organics
5. Has limited flexibility and control in comparison with competing processes
6. Has potential for vector and odor problems, although they are not as prevalent as with low-rate trickling filters
7. Long recovery times with upsets
8. Limited to 60–80% BOD_5 removal

1.2.3. Performance

Single-stage configuration with any pattern of filter effluent recirculation and primary and secondary clarification (see Fig. 14.3) has the following percent removal (1–4):

- BOD_5: 60–80%
- Phosphorus: 10–30%
- NN_4-N: 20–30%
- SS: 60–80%

The generated residual of biosolids is withdrawn from the secondary clarifier at a rate of 2,500–3,000 gal/MG (2,500–3,000 L/ML) wastewater containing 400–500 lb (226.8–317.5 kg) dry solids.

1.2.4. Design Criteria

Design criteria for high-rate trickling filters include the following (1, 3, 4):

- Hydraulic loading (with recirculation): 10–50 MG/acre/d (230–1, 150 $gal/d/ft^2$) = 9.4–46.9 $m^3/d/m^2$
- Organic loading: 900–2,600 lb BOD_5/d/acre ft (20–60 lb $BOD_5/d/1,000\,ft^3$) = 331.2–956.8 $g/d/m^3$
- Recirculation ratio: 0.5:1–4:1
- Bed depth: 3–6 ft = 0.91–1.82 m
- Dosing interval: Not more than 15 s (continuous)
- Power requirements: 10–50 hp/MG = 1.97–9.85 kW/ML
- Sloughing: continuous
- Underdrain minimum slope: 1%
- Media: Rock, 1–5 in (2.54–12.7 cm), must meet sodium sulfate soundness test

Process and mechanical reliability: The process can be expected to have a high degree of reliability if operating conditions minimize variability and the installation is in a climate where, wastewater temperatures do not fall below 13°C for prolonged periods. The process is simple to operate, and its mechanical reliability is high.

1.3. Trickling Filter, Plastic Media

Plastic media is comparatively light with a specific weight 10–30 times less than rock media. Its high void space (approximately 95%) promotes better oxygen transfer during passage through the filter than rock media with its approximate 50% void space (5–7). Because of its light weight, plastic media containment structures are normally constructed as elevated towers 20–30 ft high. Excavated containment structures for rock media can sometimes serve as a foundation for elevated towers for converting an existing facility to plastic media.

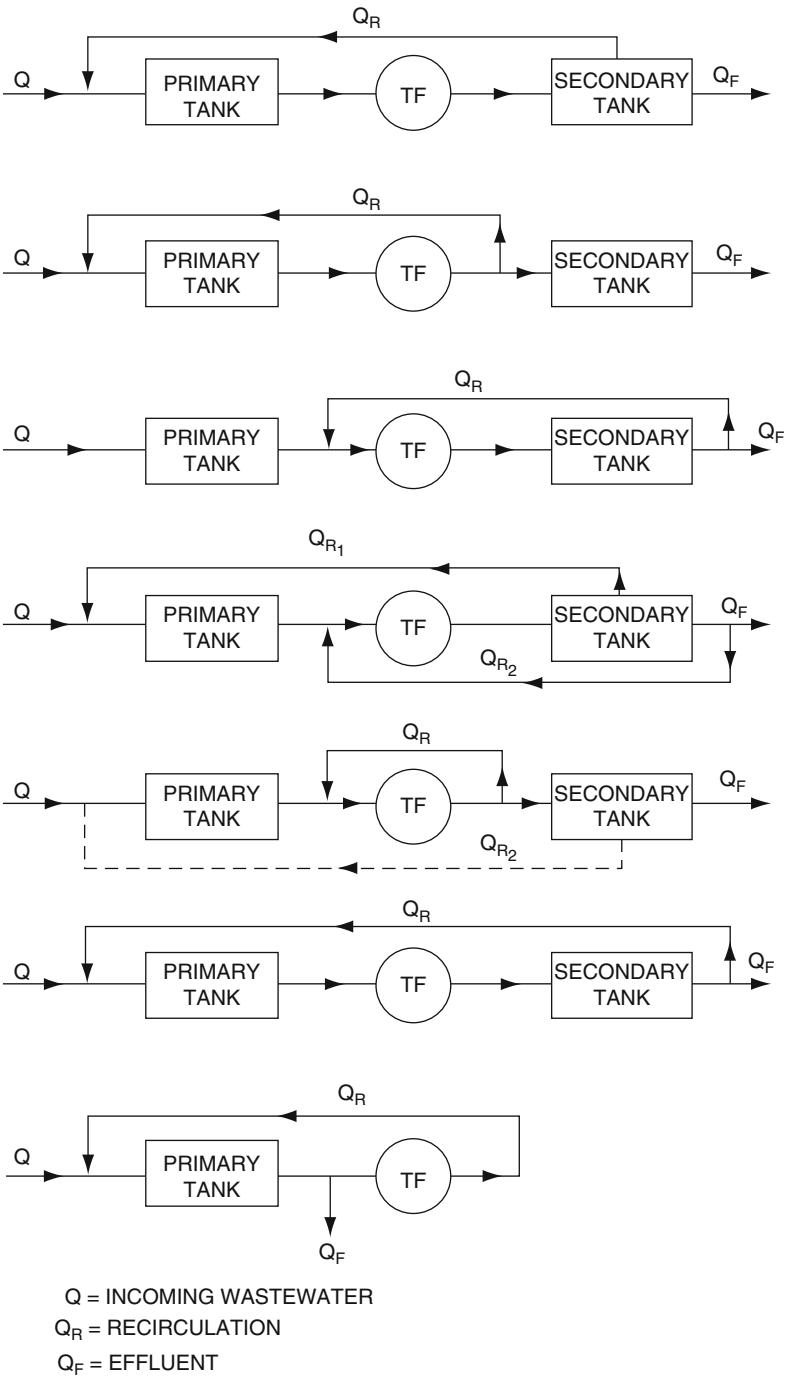

Fig. 14.3. Flow diagrams of trickling filters with various recirculation patterns (U.S. EPA).

Plastic media trickling filters can be employed to provide independent secondary treatment or roughing ahead of a second-stage biological process. When used for secondary treatment, the media bed is generally circular in plan and dosed by a rotary distributor. Roughing applications often utilize rectangular media beds with fixed nozzles for distribution.

Filter effluent recirculation is vital with plastic media trickling filters to ensure proper wetting of the media and to promote effective sloughing control compatible with the high organic loadings employed. The plastic media filters can also be used as a roughing filter at flow rates above 1, 400 gal/d/ft^2 (57.12 m^3/d/m^2) or as a separate stage nitrification process.

1.3.1. Applications

High-rate plastic media trickling filters are used in the treatment of domestic and compatible industrial wastewaters amenable to aerobic biological treatment. Industrial and joint wastewater treatment facilities may use the process as a roughing filter prior to activated sludge or other unit processes. Existing rock filter facilities can be upgraded via elevation of the containment structure and conversion to plastic media (8). The plastic media filters can also be used for nitrification following prior (first-stage) biological treatment (9).

1.3.2. Limitations

1. Vulnerable to below freezing weather
2. Recirculation may be restricted during cold weather due to cooling effects
3. Marginal treatment capability in single-stage operation
4. Is less effective in treatment of wastewater containing high concentrations of soluble organics
5. Has limited flexibility and control in comparison with competing processes
6. Has potential for vector and odor problems, although they are not as prevalent as with low rate rock media trickling filters
7. Long recovery times with upsets

1.3.3. Performance

Employing the loadings listed below for secondary treatment and using a single-stage configuration with filter effluent recirculation and primary and secondary clarification, the plastic media trickling filters can attain the following percent removal (1, 3, 4):

- BOD_5: 80–90%
- Phosphorus: 10–30%
- NH_4-N: 20–30%
- SS: 80–90%

The generated residual of biosolids is withdrawn from the secondary clarifier at a rate of 3,000–4,000 gal/MG (3,000–4,000 L/ML) of wastewater, containing 500–700 lb (226.8–317.5 kg) dry solids.

1.3.4. Design Criteria

Design criteria for plastic media trickling filters include the following (1, 3, 4, 8, 9):

- Hydraulic loading (with recirculation):
  Secondary treatment: 15–90 MG/acre/d (350–2, 050 gal/d/ft^2) = 14.3–83.6 m^3/d/m^2
  Roughing: 60–200 MG/acre/d (1, 400–4, 600 gal/d/ft^2) = 57.1–187.7 m^3/d/m^2

- Organic loading
  Secondary treatment: 450–1,750 lb BOD_5/d/acre/ft (10–40 lb BOD_5/d/1,000 ft^3) = 165–644 g/d/m^3
  Roughing treatment: 4,500–22,000 lb BOD_5/d/acre ft (100–500 lb BOD_5/d/1,000 ft^3) = 1650–8096 g/d/m^3
- Recirculation ratio: 0.5:1–5:1
- Bed depth: 20–30 ft = 6.1–9.1 m
- Dosing interval: Not more than 15 s (continuous)
- Underdrain minimum slope: 1%
- Sloughing: continuous
- Power requirements: 10–50 hp/MG = 1.97–9.85 kW/ML

Process and mechanical reliability: The process can be expected to have a high degree of reliability if operating conditions minimize variability, and the installation is in a climate where wastewater temperatures do not fall below 13°C for prolonged periods. The process is simple to operate, and its mechanical reliability is high.

2. DENITRIFICATION FILTER

2.1. Denitrification Filter, Fine Media

In the denitrification process, nitrates and nitrites in nitrified wastewater are converted to nitrogen gas by the action of facultative heterotrophic bacteria. The fine media denitrification filter is an attached growth biological process in which nitrified wastewater is passed through a pressurized submerged bed of sand or other fine filter media (up to about 15 mm in diameter) in which anoxic conditions are maintained. The nitrified wastewater contains very little carbonaceous material, and consequently requires a supplemental energy source (usually methanol) to maintain the attached denitrifying slime (1, 2). Because of the relatively fine media used, physical filtration analogous to that occurring in a pressure filter takes place. As a result, a clear effluent is produced, eliminating the need for final clarification. Backwashing is required to maintain an acceptable pressure drop. Surface loading rates may be somewhat lower than those common for pressure filtration. Development of the denitrifying slime and consequent denitrification efficiency are a function of the specific surface area of the filter, and in practice, fine media denitrification filters convert nitrates to nitrogen gas at a much higher rate than suspended growth systems. The coarser the media, the less frequent the backwashing, although the effluent may be more turbid. (See coarse media denitrification filters.)

Common modifications include the use of various media, such as garnet sand, silica sand, or anthracite coal with varying size distributions. Multimedia systems have also been used. Alternate energy sources, such as sugars, volatile acids, ethanol, or other organic compounds, as well as nitrogen-deficient materials such as brewery wastewater, may be used. An air scour may be incorporated into the backwashing cycle; however, temporary inhibition of denitrification may result. Various types of underdrains may be used. A bumping procedure (short periodic flow reversals) has been used to remove entrapped nitrogen gas bubbles produced during denitrification. Denitrification may be combined with refractory organic removal. Upflow systems utilizing fine media (sand or activated carbon) have been operated as fluidized bed reactors.

Denitrification filters are used almost exclusively to denitrify municipal wastewaters that have undergone carbon oxidation and nitrification. They may also be used to reduce nitrate in industrial wastewater.

Compared to suspended growth systems, denitrification filters have:

1. High nitrogen removal efficiency
2. Smaller structures (land use)

2.1.1. Performance

Denitrification filters are capable of converting nearly all nitrate and nitrite in a nitrified secondary effluent to gaseous nitrogen. Overall nitrogen removals of 75–90% are achievable. Suspended solid removals of up to 93% have been achieved (10).

An energy source is commonly supplied in the form of methanol. Methanol feed concentrations may be estimated using the following values per mg/L of the material at the inlet to the process.

mg/L CH_3OH per mg/L of

2.47	NO_3-N
1.53	NO_2-N
0.87	DO (Dissolved oxygen)

If supplemental energy feed rates are controlled, little excess biosolids are generated.

2.1.2. Design Criteria

- Flow scheme: Downflow (although upflow systems with different design criteria have been utilized
- Optimum pH: 6.5–7.5
- Surface loading rate: 0.5–7.0 gal/min/ft^2 = 1.22–17.08 g m^3/m^2/hr
- Media diameter (d_{50}): 2–15 mm
- Column depth: 3–20 ft (function of specific surface ft^2/ft^3 and contact time) = 0.9–6.1 m
- Backwash rate: 8–25 gal/min/ft^2 = 19.52–61 m^3/m^2/h
- Backwash cycle frequency: 0.5–4.0 d
- Specific surface: 85–300 ft^2/ft^3 = 278.8–984 m^2/m^3
- Voids: 40–50%

2.2. Denitrification Filter, Coarse Media

During denitrification, nitrates and nitrites are reduced to nitrogen gas through the action of facultative heterotrophic bacteria. Coarse media denitrification filters are attached growth biological processes in which nitrified wastewater is passed through submerged beds containing natural (gravel or stone) or synthetic (plastic) media. The process system may be a pressure system or a gravity system. Minimum media diameter is about 15 mm (1, 2).

Anaerobic or near anaerobic conditions are maintained in the submerged bed, and since the nitrified wastewater is usually deficient in carbonaceous materials, a supplemental carbon source (usually methanol) is required to maintain the attached denitrifying biomass. Because of the high void percent and low specific surface area characteristic of high porosity coarse

denitrification filters, biomass (attached slime) continuously sloughs off. As a result, the coarse media column effluent is usually moderately high in suspended solids (20–40 mg/L) requiring a final polishing step.

A wide variety of media types may be used as long as high void volume and low specific volume are maintained. Both dumped plastic media and corrugated sheet media have been used. Backwashing is infrequent and is usually done to control effluent suspended solids rather than pressure drop. Alternate energy sources, such as sugars, volatile acids, ethanol, or other organic compounds, as well as nitrogen-deficient materials, such as brewery wastes, may be used. Nitrogen gas-filled coarse media denitrification filters are a possible modification.

These filters are used almost exclusively to denitrify municipal wastewater that has undergone carbon oxidation and nitrification. They may also be used to reduce nitrate in industrial wastewater.

2.2.1. Performance

Denitrification coarse media filters are capable of converting nearly all nitrates in a nitrified secondary effluent to gaseous nitrogen. Overall nitrogen removals of 70–90% are achievable. Generally, less operator attention is required than with fine media systems (11–14).

The required amount of the most common energy source, methanol, may be estimated using the following values per mg/L of the material in the inlet to the process.

mg/L CH_3OH per mg/L of

2.47	NO_3-N
1.53	NO_2-N
0.87	DO

If supplemental carbon feed rates are controlled, little excess biosolids are generated. Biosolid production is in the range of 0.6–0.8 lb/lb NH_3-N reduced (0.6–0.8 kg/kg NH_3-N reduced).

2.2.2. Design Criteria

- Optimum pH: 6.5–7.5
- Voids: 70–96%
- Specific surface: 65–274 $ft^2/ft^3 = 213.2–898.7\ m^2/m^3$
- Nitrate loading rate: lb NO_3-N/ft^2 packing surface/d,
  Up to 0.5×10^{-4} at 5°C
  $0.2–0.8 \times 10^{-4}$ at 15°C
  $0.8–1.3 \times 10^{-4}$ at 25°C (Note: 1 lb/ft^2/d = 4.8824 kg/d/m^2)
- Surface loading rate: 2.5 and 4.1 gal/ft^2/d for a flow of 0.3 and 0.5 MGD respectively, or 0.1 and 0.167 m^3/m^2/d for a flow of 13.1 and 21.9 L/s, respectively.

3. ROTATING BIOLOGICAL CONTACTOR

The rotating biological contactor (RBC) was put into commercial use in Europe in the 1960s, and about a decade later, it was introduced USA (15). The RBC process is a fixed film biological reactor consisting of plastic media mounted on a horizontal shaft and placed

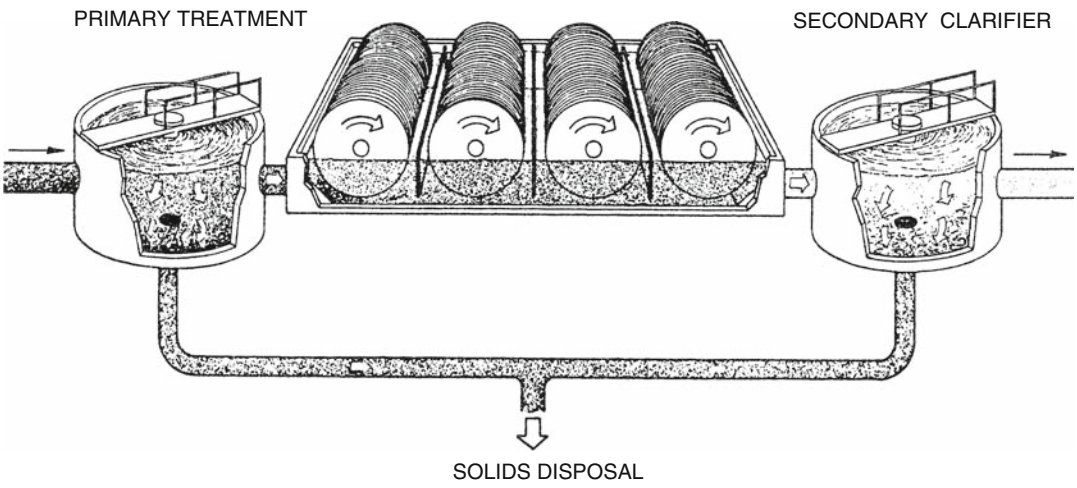

Fig. 14.4. Typical configuration of an RBC system (U.S. EPA).

in a tank. Common media forms are disc type made of Styrofoam, and a denser lattice type made of polyethylene. While wastewater flows through the tank, the media are slowly rotated, about 40% immersed, for contact with the wastewater for removal of organic matter by the biological film that develops on the media. Rotation results in exposure of the film to the atmosphere as a means of aeration. Excess biomass on the media is stripped oft by rotational shear forces, and the stripped solids are maintained in suspension by the mixing action of the rotating media (1,2,16). Multiple staging of RBCs increases treatment efficiency and aids in achieving nitrification year-round. A complete system could consist of two or more parallel trains, with each train consisting of multiple stages in series (see Fig. 14.4).

Shammas (17) has shown that the RBC process can be assumed to behave as a plug flow reactor in which first-order BOD removal and nitrification kinetics prevail (see **Eq. (1)**). The reaction rate constant, k, was reported to be 0.77/h for BOD removal and 0.5/h for nitrification (17).

$$C = C_o\, 10^{-kt} \tag{1}$$

where C is the substrate concentration (mg/L), C_o is the initial substrate concentration (mg/L), t is the time (h), and k is the reaction rate constant (1/h).

RBCs are used in the treatment of domestic and compatible industrial wastewater amenable to aerobic biological treatment in conjunction with suitable pre- and posttreatment. They can be used for nitrification, roughing, secondary treatment and polishing. There are several advantages for the system including high treatment efficiency, economy, simplicity of operation, and low O & M costs (18).

3.1. Operating Characteristics

3.1.1. Effect of Hydraulic Loading and Staging

Generally, BOD removal and nitrification increase with increasing number of stages and decreasing hydraulic loading as can be seen in Figs. 14.5–14.7. According to Shammas (19), employing six stages BOD removals of 90, 94, and 98% can be obtained for hydraulic loadings of 0.47, 0.31, and 0.16 $m^3/d/m^2$, respectively, while 61, 73, and 95% removals could be achieved for the same hydraulic loadings with three stages.

As illustrated in Fig. 14.5, BOD removals differ substantially for the early stages at various hydraulic loadings; however, they approach to closer values at the end of the sixth stage. Thus, it can be deduced that higher hydraulic loadings have a distinct dampening effect on BOD removal, especially in the early stages.

As shown in Fig. 14.6, the rate of decrease in BOD removal for a corresponding increase in hydraulic loading from 0.16 to 0.31 $m^3/d/m^2$ is sharper than the rate of decrease from 0.31 to 0.47 $m^3/d/m^2$. However, rates of decrease in BOD removals, for both ranges, decrease with increasing number of stages since the readily oxidizable BOD is already considerably removed when wastewater reaches the latter stages. Therefore, it can be concluded that an

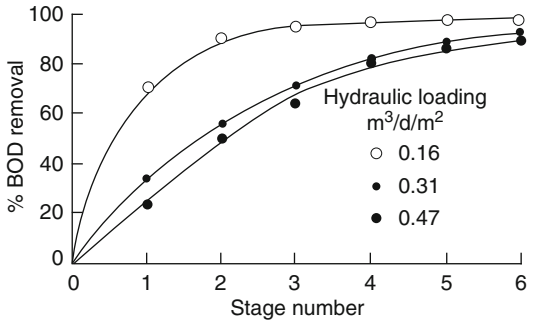

Fig. 14.5. BOD removal as a function of staging (19).

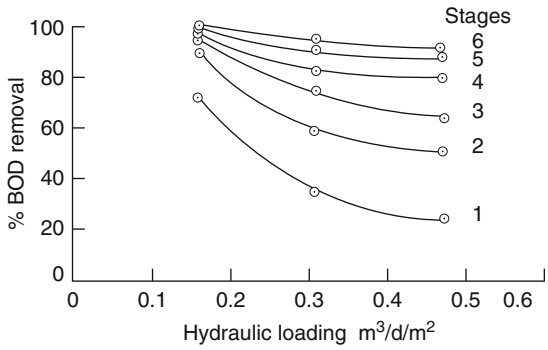

Fig. 14.6. BOD removal as a function of hydraulic loading (19).

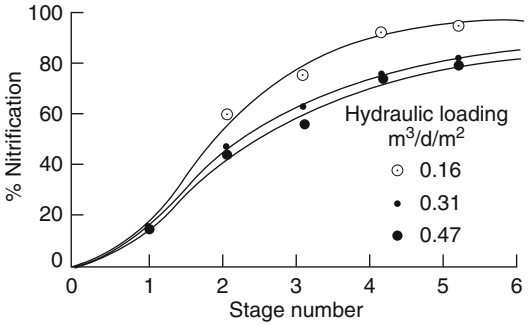

Fig. 14.7. Nitrification as a function of staging (19).

increase in number of stages will dampen the effect of the hydraulic loading, and that the effect of a shock load can be minimized by increasing the number of stages (19).

The biocontactors process is well suited for nitrification because of the natural development of nitrifying organisms in the latter stages of multistage biocontactors installations. Figure 14.7 shows that the percent decrease in ammonia-N concentration increases with increasing number of stages (19). A hydraulic loading of $0.16\,m^3/d/m^2$ could produce the highest percent decrease in ammonia-N concentration (97 and 92% at stages 6 and 4, respectively). Hydraulic loadings of 0.31 and $0.47\,m^3/d/m^2$ results in lower and somewhat equal decrease in ammonia-N concentration (an average of 85 and 75% for both at stages 6 and 4, respectively).

It is clear that the early stages are not sufficient for good nitrification. According to Shammas (19), there is a distinct change in the pattern of nitrification at stage 4 (see Fig. 14.7, indicating that a minimum of four stages will be necessary to obtain good nitrification in the system. Moreover, it is important to notice that over 90% nitrification can be achieved utilizing four stages with a hydraulic loading of $0.16\,m^3/d/m^2$, which is triple the loading recommended by Antonie (20).

3.1.2. Effect of Residence Time

Figure 14.8 shows the BOD removal efficiency as a function of residence time for different hydraulic loadings and number of stages (19). Here, the various combinations of hydraulic loadings and stages give approximately equivalent performance when compared at the same residence time. For example, 90% BOD removal is obtained for hydraulic loadings of 0.16 and $0.47\,m^3/d/m^2$ utilizing two and six stages at the same residence period of 65 min. Similarly, 95% BOD removal can be produced at 0.16 and $0.31\,m^3/d/m^2$ with three and six stages in 100 min.

Based on the results of these observations, it is concluded that in order to obtain a high BOD removal, it is essential to consider the residence time as the prime design factor (19). The performance is independent of the hydraulic loading or the number of stages as long as the combination of the two parameters produces the minimum residence time required. This optimum time varies from 75 to 100 min for 90 and 95% efficiencies, respectively.

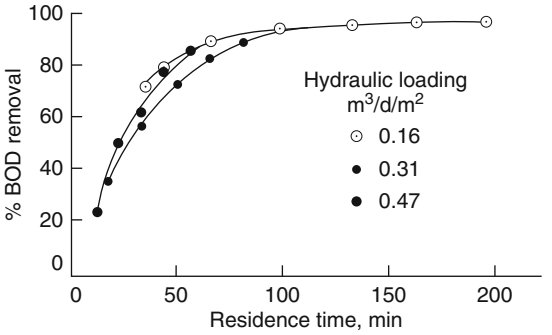

Fig. 14.8. BOD Removal as a function of residence time (19).

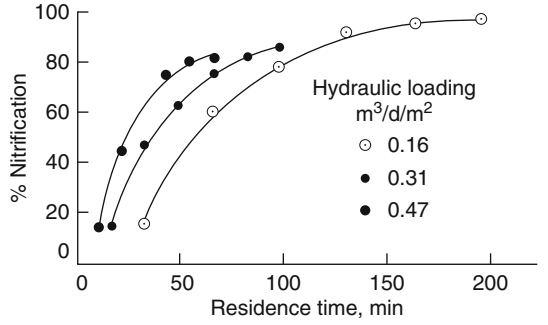

Fig. 14.9. Nitrification as a function of residence time (19).

In a similar fashion, the efficiency of nitrification as a function of residence time and for different hydraulic loadings and number of stages is given in Fig. 14.9 (19). In contrast to BOD removal, higher hydraulic loadings can result in a significantly better nitrification at the same residence time. This fact is illustrated by considering the ammonia-N removal at a residence time of 60 min. Hydraulic loadings of 0.16, 0.31, and 0.47 $m^3/d/m^2$ produces ammonia-N removals of 60, 75 and 90% utilizing two, four, and six stages, respectively. The number of stages appears to be extremely important in the case of nitrification in contrast to BOD removal where the residence time is the prime factor (19). This can be explained by the fact that higher hydraulic loadings need a greater number of stages for a given residence time, thus producing contact for the wastewater with the nitrifying biomass, which cannot compete with the bulk of other microorganism in the first few stages, while they would develop and flourish in the latter stages where the BOD has already been reduced.

3.1.3. Effect of Influent BOD Concentration

The effect of influent BOD concentrations of 270 and 700 mg/L was investigated at the same hydraulic loading and disc speed. As shown in Fig. 14.10, identical BOD removals greater than 95% are obtained for the last four stages.

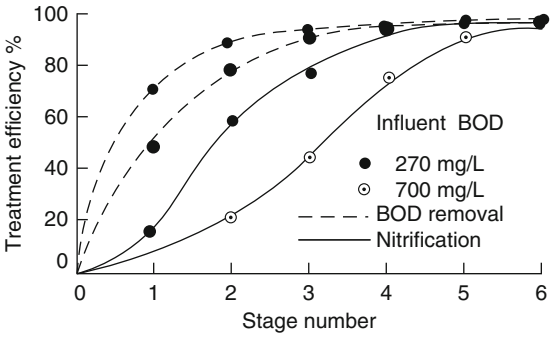

Fig. 14.10. Effect of influent BOD on treatment efficiency (19).

Figure 14.10 also depicts the effect of influent BOD concentration on nitrification. It is obvious that nitrification is much better at lower BOD concentration. However at stage 6 when the BOD drops to 6 and 16 mg/L (for BOD influents of 270 and 700 mg/L), ammonia oxidation is almost complete. These results reinforce the previous findings on the importance of staging in achieving high nitrification efficiencies (19).

3.1.4. Effect of Disc Speed

The disc speed is usually maintained near 3.5 rpm (peripheral velocity of 0.092 m/s). Lower speeds decrease the sloughing of biomass and cause clogging; while higher speeds do not produce any improvement in efficiency (19). Further information on contribution factors can be found in other references (21–23).

3.2. Performance

The common four-stage system configuration with final clarifier and preceded by primary treatment can attain the following percent removals:

- BOD_5: 60–90%
- SS: 80–90%
- Phosphorus: 10–30%
- NH_4-N: up to 95%

The rate of biosolids production, which is removed in the secondary clarifier is 3,000–4,000 gal/MG (3000–4000 L/ML) of wastewater, 500–700 lb dry solids/MG (60–84 g dry solids/m^3) wastewater.

3.3. Design Criteria

The organic loadings for RBCs, as recommended by South Dakota Department of Environmental & Natural Resources (24), are as follows:

- The organic loading to the first stage should be in the range of 3.5–6.0 lb total $BOD_5/1,000\ ft^2/d$ or 1.5–2.5 lb soluble $BOD_5/1,000\ ft^2/d$ = 17087–29292 kg total $BOD_5/km^2/d$ or 7323–12205 kg soluble $BOD_5/km^2/d$.

- For average conditions, the design loading should not exceed 2.5 lb soluble $BOD_5/1,000\,ft^2/d$ (12205 kg soluble $BOD_5/km^2/d$) on the first stage shaft(s) of any treatment train.
- For peak conditions, the design loading should not exceed 2.0 lb of soluble $BOD_5/1,000\,ft^2/d$ (9764 kg soluble $BOD_5/km^2/d$) for the third shaft(s) in a treatment train.
- For average conditions, the overall system loading shall not exceed 0.6 lb of soluble $BOD_5/1,000\,ft^2/d$ (2929 kg soluble $BOD_5/km^2/d$). This soluble BOD_5 loading to all shafts should be used to determine the total number of shafts required.

Other design criteria as reported in the literature (17–23) are given below:

- BOD loading:
  - Without nitrification: 30–60 lb $BOD_5/d/1,000\,ft^3$ media (480.5–961.0 $g/d/m^3$)
  - With nitrification: 15–20 lb $BOD_5/d/1,000\,ft^3$ media (240.2–320.4 $g/d/m^3$)
- Hydraulic loading:
  - Without nitrification: 0.75–1.5 $gal/d/ft^2$ media surface area (0.03–0.06 $m^3/d/m^2$)
  - With nitrification: 0.3–0.6 $gal/d/ft^2$ media surface area (0.012–0.024 $m^3/d/m^2$)
- Number of stages per train: 1–4 depending on treatment objectives
- Number of parallel trains: Recommended at least 2
- Peripheral velocity:
  - 60 ft/min for mechanically driven (18.3 m/min)
  - 30–60 ft/min for air driven (9.1–18.3 m/min)
- Media surface area:
  - 20–25 ft^2/ft^3 for typical discs (65.6–82 m^2/m^3)
  - 30–40 ft^2/ft^3 for standard lattice discs (98.4–131.2 m^2/m^3)
  - 50–60 ft^2/ft^3 for high-density lattice discs (164–196.8 m^2/m^3)
- Percent media submerged: 40%
- Tank volume: 0.12 gal/ft^2 of disc area (0.004896 m^3/m^2)
- Detention time
  - 40–120 min without nitrification
  - 90–250 min with nitrification
- Secondary clarifier overflow rate: 500–800 $gal/d/ft^2$
- Power:
  - 3.0–5.0 HP consumed/25 ft shaft (2.2–3.7 kW/7.6 m shaft)
  - 5.0–7.5 HP connected/25 ft shaft (3.7–5.6 kW/7.6 m shaft)

4. FLUIDIZED BED REACTOR

Fluidized bed reactors (FBR), Packed bed reactors (PBR), and biological aerated filters (BAF) represent attached growth processes that have been utilized to some extent for nitrification of municipal wastewaters. Unlike trickling filters, the hydraulic design of these systems is such that the media are submerged in the reactor liquid. In packed bed reactors and biological aerated filters, the media are stationary during normal operation, held in place by gravity. In the fluidized bed reactor, the media are expanded or fluidized as the incoming flow passes upward through the reactor.

4.1. FBR Process Description

In the conventional biological fluidized bed reactor, often referred to as an expanded bed reactor, wastewater or wastewater plus recycled effluent is introduced at the bottom of the reactor at a hydraulic loading rate or upflow velocity sufficient to expand the bed media, resulting in a fluidized state. The fluidized media particles provide a vast surface area for biological growth, in part leading to the development of a biomass concentration approximately five to ten times greater than that normally maintained in a conventional suspended growth reactor (25). To date, the media employed in most full-scale fluidized bed reactors have either been silica sand or granular activated carbon.

The mechanical components and subsystems critical to the development of fluidized bed commercial systems are (26):

(a) The device or method to distribute the influent flow to the reactor
(b) The device or method to transfer oxygen in a controlled fashion to the fluidized bed reactor in aerobic applications of the technology. The oxygenation system is particularly critical in the treatment of wastewaters containing medium to high concentrations of oxygen demanding material (i.e., O_2 requirements greater than 25 mg/L)
(c) The device or method to control the expansion of the fluidized bed due to biofilm growth. The bed height control system is particularly critical in treatment applications where the net yield of biomass is significant. Further details concerning the critical components have been presented elsewhere (27).

Although the development of water and wastewater systems using a fluidized bed of biomass can be traced back to the 1940s in England (28), media-based fluidized bed reactors were not developed until the early 1970s. Researchers at Manhattan College in New York, at the EPA Municipal Environmental Research Laboratory in Cincinnati, OH, and at the Water Research Centre in Medmenham, England, can be credited for the initial application of media-based fluidized bed reactors to water and wastewater treatment. The Manhattan College researchers were granted a U.S. patent in 1974 (assigned to Ecolotrol, Inc.) for the application of the fluidized bed process configuration to "denitrifying wastewater" (29). In a paper published in 1970 by researchers from the University of Michigan, biological activity was observed in expanded-bed activated carbon reactors and was believed to be the reason for the observed nitrate reduction (30).

The ability of the biological fluidized bed process configuration to intensify biological reaction rates through accumulation of high concentrations of active biomass has attracted attention for many years (31). The results from laboratory and field pilot scale studies have consistently illustrated the technical advantages of the fluidized bed over most other suspended and attached growth reactor configurations in many wastewater treatment applications. In 1981, a comprehensive account of ongoing fluidized bed process development activities was published based on a 1980 seminar held in Manchester, England (32). Although hailed at that time as the most significant development in the wastewater treatment field in the last 50 years, it also was claimed that no full-scale plants were yet in operation. Since that time, even though more than 70 commercial, fluidized bed reactors have been installed in North America and Europe, wider use of the technology has been hampered by such factors as (33):

(a) Mechanical scale-up issues
(b) Slow development of economically attractive system configurations, and
(c) Proprietary constraints

According to a 1991 state-of-the-art review of fluidized beds for water and wastewater treatment, the technology was being applied largely for industrial versus municipal wastewater treatment at current operating full-scale installations in North America and Europe (33). Although full-scale fluidized bed industrial systems are operating under conditions that result in nitrification (34), few, if any, systems have been installed for nitrification of municipal wastewaters on a full scale. A limited number of reactors have been installed for denitrification of municipal wastewater (35).

4.2. Process Design

Information useful for the process design of full-scale systems for nitrification of municipal wastewater derived from the results of fluidized bed pilot plant studies (36–48) is summarized as follows:

(a) A half-order model appears appropriate to describe the kinetics of ammonium oxidation in fluidized bed reactors under nonlimiting DO conditions
(b) The volumetric removal rate and the specific ammonium oxidation rate decrease significantly at low reactor ammonium concentrations.
(c) The fluidized bed hydraulic retention time required to achieve nitrification down to ammonium levels of 2 mg/L or less ranges from 10 to 40 min. This HRT is for treatment of municipal wastewaters containing less than 50 mg/L of $CBOD_5$ and approximately 20 mg/L of oxidizable nitrogen compounds, and providing that the reactor is designed to promote the buildup of at least 8.5 g/L of volatile attached solids and that nonlimiting DO conditions are achieved. The actual HRT required will depend on such factors as the concentration of carbonaceous BOD in the wastewater, the system hydraulics (i.e., plug flow versus complete mixing conditions), and the reactor temperature and pH conditions.

If the use of the fluidized bed for nitrification is being considered, onsite piloting is recommended given the limited amount of full-scale operating and performance information on this application.

4.3. Applications

The fluidized bed reactor is more commonly used for industrial wastewater rather than municipal wastewater. Concerns over municipal applications have included mechanical scale-up factors, proprietary constraints, and economically unattractive system appurtenances (49). However, there are successful municipal applications; Table 14.1 lists the design parameters and loadings of four industrial and municipal installations with fluidized bed reactors operating in the denitrification mode (25).

The principal commercial suppliers of fluidized bed systems are Dorr-Oliver, Envirex, and Ecolotrol. Both Dorr-Oliver and Envirex systems were developed on the basis of Ecolotrol process patents. Currently, Envirex is the only manufacturer actively marketing the fluidized bed reactor for denitrification applications in the United States. Table 14.2 summarizes the types of reactors in use (25).

Table 14.1
Design parameters and loadings of denitrification FBR plants[a] (26)

Parameter	Facility			
	Pensacola[b,c]	Reno-Sparks	Rancho, CA[c]	IBM[c]
Mean wastewater flow, L/s	1,052	1,883	263	113
Mean wastewater flow, mgd	24	43	6[d]	1[d]
Maximum wastewater flow, L/s	1,490	2,400		
Maximum wastewater flow, mgd	34	55		
Influent NO_3^--N, mg/L	20	18	21	54
Effluent NO_3^--N, mg/L	< 6	2	2.5	8
Design wastewater temperature, °C	18	13	22	10
Estimated reactor biomass, mg/L VSS	NA	18,000	28,000	NA
Hydraulic retention time,[e] min	8.5	13.8	10	26
Hydraulic loading rate,[f] $m^3/m^2/d$	672	550	336	578
Hydraulic loading rate,[f] gpd/sq ft	11.4	9.3	0.8	1.3
Estimated settled sand depth, m	1.8	2.4	1.2	1.5
Estimated settled sand depth, ft	6	8	4	5
Fluidized bed height, m	4	4.9	2.4	2.7
Fluidized bed height, ft	13	16	8	9

[a] Source: US EPA
[b] Modified design as developed by Dorr-Oliver, Inc.
[c] No longer operated for denitrification.
[d] Equalization provided to achieve a constant wastewater flow rate.
[e] Based on mean wastewater flow and fluidized bed/empty bed volume.
[f] Based on total flow to the reactor (plant flow plus recycle).

Table 14.2
Types of FBRs in use (26)

Oxitron system
– Developed by Dorr-Oliver
– System based on Ecolotrol process patents
– Uncertain regarding system marketing in North America
– Dorr-Oliver Europe marketing systems in Europe
Rex aerobic fluidized bed process, anaerobic and biological denitrification configuration
– Developed by Envirex/Ecolotrol based on Ecolotrol process patents
– Sold in North America by Envirex
Custom engineered systems
– Developed by consulting engineering firms
– Normally designed and operated under conditions falling outside the limits of Ecolotrol patents

The principle of the fluidized bed reactor is the same, regardless of the application. Examples of applications to the remediation of groundwater to remove various organic contaminants and produce cleaner and safer water supplies can be found in the literature (50–55).

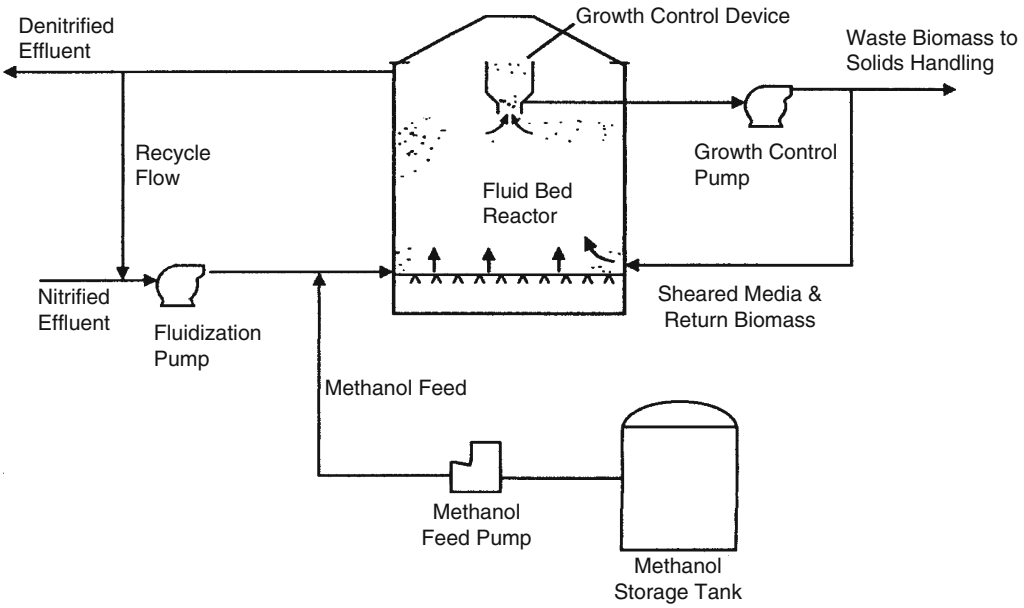

Fig. 14.11. Flow diagram of upflow fluidized bed system (26).

4.4. Design Considerations

The upflow fluidized bed system usually consists of a reactor vessel in the form of an above-ground steel and fiberglass tower or in-ground concrete reactors. The flow rate and strength of waste determines the size of the reactor vessel. The reactor size is dependent on temperature; at 15°C(59° F), the design loading rate is 6,420 kg NO_3^--N/1, 000 m^3/d (400 lb/ 1, 000 ft^3/d) (51).

When the fluidized bed system is operated for denitrification, methanol is fed to the nitrified influent by injection into the recycle line (see Fig. 14.11). The reactor operates as a plug flow process; however, the high recycle ratio of reactor effluent to plant flow (10:1–20:1 for high strength waste treatment and 2:1–5:1 for municipal denitrification) emulates a complete mix system. The high recycle ratio also helps protect the reactor from shock loads and is required to achieve bed fluidization. The amount of recycle is dictated by a maximum allowable fluid-bed height, structural considerations often control bed height (57–60).

4.5. Case Study: Reno-Sparks WWTP

A flow diagram for the 1,753-L/s (40-MGD) Reno-Sparks Wastewater Treatment Plant is shown in Fig. 14.12. The treatment plant, which serves the cities of Reno and Sparks in Nevada, consists of preliminary treatment, primary treatment, phosphorus and BOD removal in a sidestream phosphorous-removal system, nitrification biotowers, denitrification upflow fluidized bed reactors, postaeration, effluent filtration and disinfection. The solids handling system consists of thickening, anaerobic digestion, and dewatering.

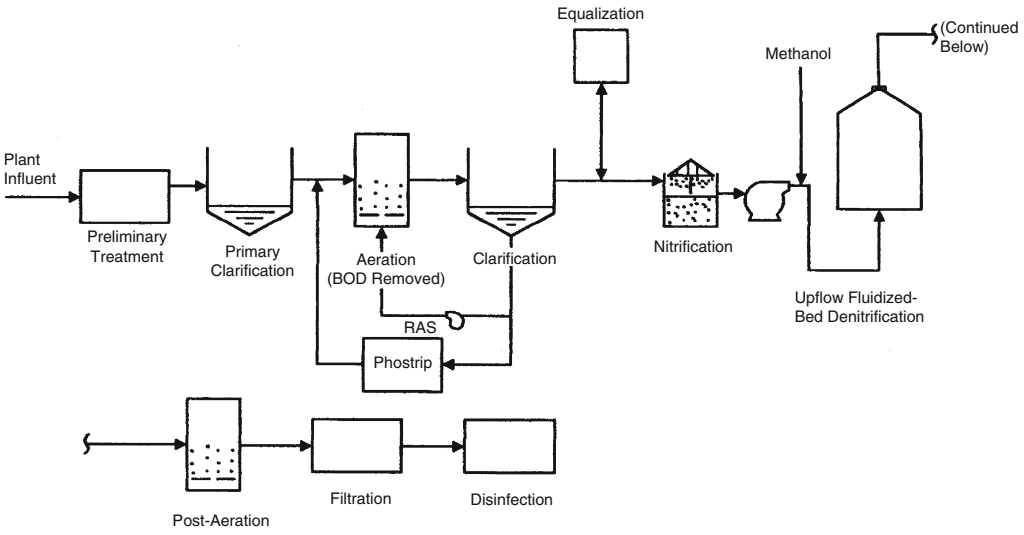

Fig. 14.12. Flow diagram of Reno-Sparks wastewater treatment plant (26).

The denitrification system consists of four upflow fluidized bed towers measuring approximately 8.2 m (27 ft) in diameter by 6.2 m (20.5 ft) high. The hydraulic residence time at average daily flow is 13.8 min, and the solids residence time (SRT) is 8.5 d. The denitrification system, manufactured by Envirex, was designed to produce effluent with a nitrate level of 2 mg/L. A summary of monthly plant operating data is provided in Table 14.3. The data indicate that the Reno-Sparks plant has consistently met its effluent requirements, with an average effluent ammonia level of 0.16 mg/L and a NO_x-N level of 0.29 mg/L. The plant's efficiency in removing total nitrogen has been 94%. The removal rate of the fluidized bed reactors has been 6.4 kg NO_x-N/m^2/d (1.3 lb/ft^2/d), and the plant has regularly produced an effluent TN of less than 3 mg/L and an average effluent TN of 1.78 mg/L. The one event over 3 mg/L TN was 3.55 mg/L.

5. PACKED BED REACTOR

5.1. Aerobic PBR

A packed bed reactor, often referred to as a submerged filter, contains a stationary bed of media, which provides support for biological growth. The influent wastewater (or wastewater plus recycled effluent) is normally introduced at the bottom of the reactor through a flow distribution system. Methods utilized to supply the necessary oxygen to support biomass growth have included direct introduction of air (61) or high-purity oxygen (62) into the bottom of the reactor through a gas distribution system or injection of air or oxygen into the feed line entering the reactor. Alternatively high-purity oxygen has been dissolved in the feed stream in an oxygenation device prior to the feed entering the reactor (61).

Table 14.3
Reno-Sparks wastewater treatment plant: monthly performance data (26)

Month	Plant fluent					Denitrification process influent		Denitrification process effluent		Final plant effluent				
	Flow		BOD_5	NH_4^+-N	TN	NH_4^+-N	NO_x-N	TSS	NO_x-N	BOD	TSS	NH_4^+-N	NO_x-N	TN
	L/s	MGD	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
JAN 90	1,133	25.86	167			0.37	14.44		2.12	5	5	0.13	0.79	2.53
FEB 90	1,153	26.30	171			0.53	14.58		3.91	8	5	0.24	0.43	2.25
MAR 90	1,174	26.79	178			0.31	14.80		0.80	5	4	0.27	0.88	2.79
APR 90	1,156	26.37	177			1.37	14.21		0.82	6	2	0.29	0.90	3.35
MAY 90	1,169	26.66	183			0.67	12.84		0.19	5	3	0.08	0.15	1.38
JUN 90	1,221	27.87	175			0.35	14.02		0.06	3	2	0.11	0.16	1.43
JUL 90	1,202	27.42	152			0.30	14.07		0.04	3	2	0.10	0.06	1.11
AUG 90	1,233	28.14	164			0.91	13.70		0.29	6	10	0.32	0.14	1.82
SEP 90	1,211	27.64	168			0.56	14.18		0.12	7	18	0.41	0.11	2.50
OCT 90	1,175	26.81	149			0.15	11.03		0.03	3	2	0.05	0.01	1.01
NOV 90	1,144	26.10	162			0.37	13.17		0.10	4	3	0.19	0.07	1.26
DEC 90	1,192	27.20	150			1.13	13.92		0.22	4	6	0.33	0.37	2.00
JAN 91	1,168	26.64	132	21.1	32.3	0.45	14.04	22	0.24	3	4	0.17	0.35	1.64
FEB 91	1,122	25.60	130	22.2	32.3	0.46	14.26	20	0.16	3	3	0.18	0.28	1.58
MAR 91	1,149	26.21	135	22.5	32.2	0.35	14.88	18	0.39	3	4	0.10	0.42	1.70
APR 91	1,103	25.17	142	22.7	32.2	0.16	15.56	20	0.31	4	4	0.02	0.28	1.53
MAY 91	1,137	25.95	186	22.0	31.9	0.59	15.07	21	0.17	4	4	0.03	0.14	1.47
JUN 91	1,171	26.72	167	21.0	31.9	0.08	13.72	17	0.03	2	4	0.02	0.03	1.18
JUL 91	1,210	27.36	160	20.1	31.6	0.06	13.85	13	0.08	3	4	0.03	0.03	1.01
Average	1,169	26.67	160	21.7	32.1	0.48	14.02	19	0.53	4	5	0.16	0.29	1.78

In 1975, the EPA Process Design Manual for Nitrogen Control noted that packed bed reactors for nitrification were a comparatively recent development, having progressed from laboratory and pilot status to the point of commercial availability (63). Since that time, packed bed reactors have been widely applied for commercial treatment of industrial wastewaters and contaminated ground waters. Despite continuing interest in packed bed reactors for nitrification of municipal wastewaters (61–66) and additional pilot studies, packed bed reactors have not been widely applied on a full scale. The lack of information clearly demonstrating significant advantages of the technology relative to alternatives for this application has limited the acceptance of packed bed reactors at the full-scale level for municipal wastewater treatment.

Several types of media including stones, gravel, anthracite, and random plastic media, had been successfully utilized in pilot plant studies of packed bed reactors. In more recent studies, the media utilized have normally been either random or corrugated plastic structures with high void volume (61–66). The use of such media may eliminate the need for backwashing to control the buildup of reactor SS. If solids buildup is not prevented or controlled, the hydraulic integrity of the reactor will be compromised. Design and operating strategies that minimize the buildup of reactor SS include:

(a) The use of media with a high void volume (greater than 90%)
(b) The supply of oxygen by the direct introduction of air into the bottom of the reactor

5.2. Anaerobic Denitrification PBR

5.2.1. Coarse Media Beds

When PBRs are used for denitrification, nitrates and nitrites are reduced to nitrogen gas through the action of facultative heterotrophic bacteria. Coarse media denitrification filters are attached growth biological processes in which nitrified wastewater is passed through submerged beds containing natural (gravel or stone), granular activated carbon (GAC), or synthetic (plastic) media. The systems may be pressure or gravity. Minimum bed media size is about 15 mm. Anaerobic or near anaerobic condition is maintained in the submerged bed, and since the nitrified wastewater is usually deficient in carbonaceous materials, a supplemental carbon source (usually methanol) is required (Fig. 14.13) to maintain the attached denitrifying slime (67). Because of the high void percent and low specific surface area characteristic of high porosity coarse denitrification filters, biomass (attached slime) continuously sloughs off. As a result, the coarse media column effluent is usually moderately high in suspended solids (20–40 mg/L), requiring a final polishing step.

A wide variety of media types may be used as long as high void volume and low specific volume are maintained. Both dumped plastic media (Fig. 14.14) and corrugated sheet media have been used. Backwashing is infrequent and is usually done to control effluent suspended solids rather than pressure drop. Alternate energy sources, such as sugars, volatile acids, ethanol, or other organic compounds, as well as nitrogen-deficient materials such as brewery wastes, may be used. Nitrogen gas-filled coarse media denitrification filters are a possible modification.

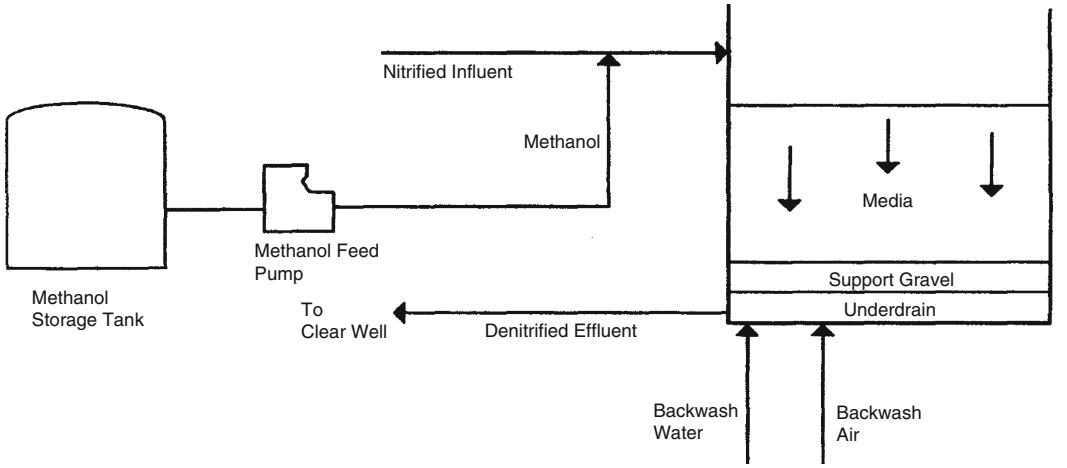

Fig. 14.13. Flow diagram of packed bed reactor system (26).

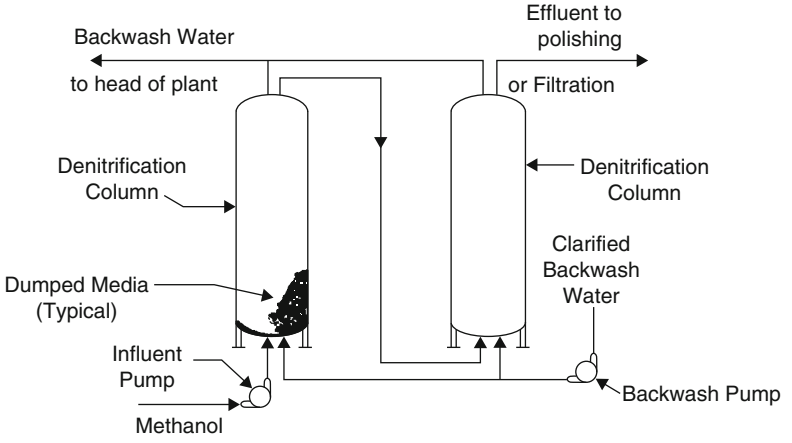

Fig. 14.14. PBR system with coarse media denitrification columns (67).

5.2.2. Fine Media Beds

The fine media denitrification filter is an attached growth biological process in which nitrified wastewater is passed through a pressurized submerged bed of sand or other fine filter media (up to about 15 mm in diameter) in which anoxic conditions are maintained. Because of the relatively fine media used, physical filtration analogous to that occurring in a pressure filter takes place. As a result, a clear effluent is produced, eliminating the need for final clarification (67). Backwashing is required to maintain an acceptable pressure drop. Surface loading rates may be somewhat lower than those common for pressure filtration. Development of the denitrifying slime and consequent denitrification efficiency are a function of the specific surface area of the filter, and in practice fine media denitrification filters convert nitrates to

nitrogen gas at a much higher rate than suspended growth systems. The coarser the media, the less frequent the backwashing, although the effluent may be more turbid.

Common modifications include the use of various media such as garnet sand, silica sand, anthracite coal, or activated carbon with varying size distributions. Multimedia systems have also been used. Alternate energy sources, such as sugars, volatile acids, ethanol, or other organic compounds, as well as nitrogen-deficient materials such as brewery wastewater, may be used. An air scour may be incorporated into the backwashing cycle; however, temporary inhibition of denitrification may result. Various types of underdrains may be used. A bumping procedure (short periodic flow reversals) has been used to remove entrapped nitrogen gas bubbles produced during denitrification. Denitrification may be combined with refractory organic removal. Upflow systems utilizing fine media (sand or activated carbon) have been operated as fluidized bed reactors.

5.3. Applications

PBRs are used mostly for nitrogen removal by biological nitrification–denitrification of municipal wastewater that has undergone carbon oxidation. Examples of packed bed denitrification treatment plants are listed in Table 14.4. Similar units are also used to reduce nitrate in industrial wastewater systems (67).

5.4. Design Criteria

The design criteria for both coarse and fine media PBRs, as stated in US EPA manuals (63, 67), are given below.

5.4.1. Coarse Media Beds

(a) Optimum pH = 6.5–7.5
(b) Voids = 70–96%
(c) Specific surface = 65−274 ft^2/ft^3 = 213.2−898.7 m^2/m^3
(d) Media size = greater than15 mm
(e) Loading rate in lb NO_3-N/ft^2 packing surface/d is a function of temperature up to 0.5×10^{-4} at 5°C, 0.2–0.8 $\times 10^{-4}$ at 15°C and 0.8–1.3 $\times 10^{-4}$ at 25°C. Here 1 1b/ft^2/d = 4.88 kg/d/m^2
(f) Surface loading rate = 2.5 gal/ft^2/d for a flow of 0.3 MGD and 4.1 gal/ft^2/d for a flow 0.5 MGD. Here 1 gal/ft^2/d = 0.0408 m^3/m^2/d; 1 MGD = 43.8 L/s
(g) Amount of the most common energy source, methanol, required may be estimated at 2.47 mg/L CH_3OH per mg/L of NO_3-N and 1.53 mg/L CH_3OH per mg/L NO_2-N in the inlet to the process

5.4.2. Fine Media Beds

(a) Flow Scheme: Downflow (although upflow systems with different design criteria have been utilized)
(b) Optimum pH = 6.5–7.5
(c) Voids = 40–50%
(d) Specific surface = 85–300 ft^2/ft^3 = 278.8–784 m^2/m^3
(e) Media diameter (d_{50}) = 2–15 mm
(f) Surface loading Rates = 0.5–7.0 gpm/ft^2 = 1.22–17.08 m^3/h/m^2
(g) Column depth = 3–20 ft (function of specific surface and contact time) = 0.91–6.10 m
(h) Backwash rate = 8–25 gpm/ft^2 = 19.52–61 m^3/h/m^2
(i) Backwash cycle frequency = 0.5–4.0 d

Table 14.4
Installation list of Packed Bed Denitrification Systems (26)

Faculty and location	Description of packed-bed denitrification system	Capacity	
		L/s	MGD
Tampa, Florida Hookers Point AWTP	Twelve 97 m^2 (1,050 sq ft) fillers Nineteen 93 m^2 (1,000 sq ft) filters	4,208	96.0
Seminole County, Florida NW Area Regional WW Facility Expansion	Two 46 m^2 (500 sq ft) filters	110	2.5
Port Orange, Florida	Six 52 m^2 (560 sq ft) filters	351	8.0
Hillsborough County, Florida Valrico Wastewater Facility	Three 46 m^2 (500 sq ft) filters	132	3.0
U.S. Home Brandon, Florida	One 19 m^2 (200 sq ft) filters	33	0.75
Purity Farms Clearwater, Florida	One 9.3 m^2 (100 sq ft) filters	10	0.23
Hillsborough County, Florida Dale Mabry AWTP	Five 60 m^2 (650 sq ft) filters	264	6.0
Piney Orchards, Maryland	Four 9.3 m^2 (100 sq ft) filters	53	1.2
Hillsborough County, Florida Falkenburg RD AWTP	Five 46 m^2 (500 sq ft) filters	264	6.0
Altamonte Springs, Florida	Seven 56 m^2 (600 sq ft) filters deep-bed filters for tertiary filtration, denitrification, and virus control of municipal sewage treatment plant effluent	110 548	2.5 (avg.) 12.5 (peak)
Florida Cities Water Co. Fiesta Village Fort Myers, Florida	Four 37 m^2 (400 sq ft) filters for nitrate reduction and SS removal	96 220	2.2 (avg.) 5.0 (peak)
Kanapaha Wastewater Treatment Plant Gainesville, Florida	Six 46 m^2 (500 sq ft) filters	308 770	7.0 (avg.) 17.5 (peak)
Parkland III Expansion Islip, New York	Deep-bed gravity denitrification effluent polishing system including four 5.6 m^2 (60 sq ft)	11	0.26
Fairfield Village, New York	Two 5.6 m^2 (60 sq ft) deep-bed sand filters for effluent polishing and denitrification	4	0.085
Southhampton Hospital Southhampton, New York	Two 4.7 m^2 (60 sq ft) deep-bed sand filters for effluent polishing and denitrification	4	0.1
Blue Ridge Condo. Medford	One deep-bed sand filter system. System includes three deep-bed gravity filler cells 5.6 m^2 (60 sq ft) each	9	0.2

(*Continued*)

Table 14.4
(Continued)

Faculty and location	Description of packed-bed denitrification system	Capacity L/s	Capacity MGD
Brookhaven, New York			
Parkland III	One deep-bed gravity filtration system for effluent polishing and denitrification. System includes four deep-bed filter cells 5.6 m^2 (60 sq ft) each	28	0.65
Islip, New York			
Parr Village	Three 48 m^2 (52 sq ft) deep-bed sand filters	20	0.45
Yaphank, New York			

(j) Amount of the most common energy source, methanol, required may be estimated at 2.47 mg/L CH_3OH per mg/L of NO_3-N and 1.53 mg/L CH_3OH per mg/L NO_2-N in the inlet to the process.

5.5. Performance

As with trickling filters, the efficiency and performance of nitrifying packed bed reactors can be expected to correlate to the effective surface area for biofilm growth, although growth of active nitrifiers in the voids of the media may affect this correlation. Thus, both the surface loading and the volumetric loading are likely to influence nitrification efficiency and performance in packed bed reactors. Other factors, such as the concentration of DO, $CBOD_5$, and ammonium in the reactor, environmental conditions (i.e., temperature and pH), and media characteristics (i.e., surface-to-volume ratio and percent voids), will influence the correlations between loading and nitrification performance. Although surface and volumetric loading information applicable to the design of packed bed reactors for nitrification of municipal wastewaters is available (61–65), onsite piloting is recommended if the technology is being considered for use on a full scale.

Packed bed reactors are capable of converting nearly all nitrates in a nitrified secondary effluent to gaseous nitrogen. Overall nitrogen removals of 70–90% are achievable. In fine media beds Suspended solids removals of up to 93% have been achieved. Under controlled pH, temperature, loading and chemical feed high levels of reliability are achievable. Studies on the effects of environmental factors, modeling and kinetics in full scale submerged denitrification PBRs can be found in refs. (68) and (69).

With controlled supplemental carbon feed rates, little excess sludge is generated. Sludge production varies between 0.6 and 0.8 lb/lb NH_3-N reduced.

5.6. Case Study: Hookers Point WWTP (Tampa, Florida)

Operating data for downflow packed bed systems are shown in Table 14.5. The 4,208-L/s (96 MGD) Hookers Point Wastewater Treatment Plant (WWTP) includes preliminary treatment, primary treatment, biological treatment, postaeration, and effluent disinfection.

Table 14.5
Operating Data for downflow Packed Bed Reactor Systems (26)

Facility	Florida location	Capacity L/s	Capacity MGD	Average rate $m^3/m^2/d$	Average rate gpm/sq ft	Number of denit. filters	Filter size	Media depth m	Media depth in.	Media size, mm
Hookers Point	Tampa	4,208	96.0	123	2.1	20	3 m × 32 m (10 ft × 105 ft)	1.47	54	2.3
Fiesta Village	Ft. Myers	220	5.0	117	2.0	4	3 m × 13.4 m (10 ft × 44 ft)	1.83	72	3.0
Altamonte Springs	Altamonte	548	12.5	123	2.1	7	3 m × 18.3 m (10 ft × 60 ft)	1.83	72	Dual media
Faulkensand Road, Hillsborough Co.	Tampa	264	6.0	29	0.5	5	3 m × 15.2 m (10 ft × 50 ft)	1.22	48	3.0
Dale Mabry	Tampa	264	6.0	123	2.1	5	3 m × 19.8 m (10 ft × 65 ft)	1.83	72	2.3
Port Orange	Port Orange	526	12.0	123	2.1	7	3 m × 17.1 m (10 ft × 56 ft)	1.07	42	1.8

Note: All plants have a 3 mg/L permit limit

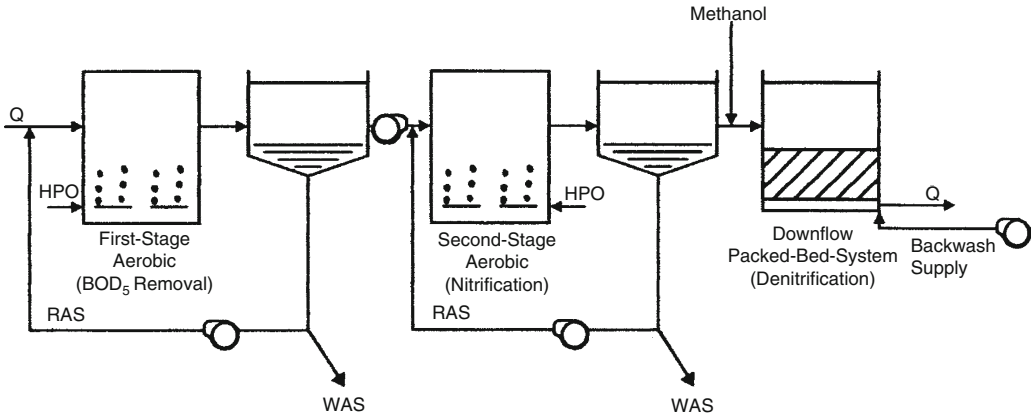

Fig. 14.15. Flow diagram of Hookers point advanced wastewater treatment plant (26).

The biological treatment system includes two-stage carbonaceous oxidation/nitrification using high-purity oxygen and a separate-stage downflow packed bed denitrification system with methanol feed. A flow diagram is shown in Fig. 14.15.

The downflow packed bed denitrification system consists of 20 filters measuring 3 m × 32 m (10 ft × 105 ft). Each filter is filled with 142 cm (56 in.) of coarse sand (2.3 mm), loaded at an average rate of 59–117 $m^3/m^2/d$ (1–2 gpm/ft^2) and having an empty bed contact time of 45 min at average flow.

The Hookers Point WWTP receives domestic wastewater, with a 30% contribution from breweries (70). The influent wastewater has a BOD_5 of 224 mg/L, TSS of 221 mg/L, and TKN of 32 mg/L. The current effluent limits of the plant are 5 mg/L for BOD_5 and TSS, 3 mg/L for TN on an annual average basis, and 7.5 mg/L for total phosphorous (TP). The average month's effluent is below 3 mg/L TN 83% of the time, with an average over 3-year period of 2.33 mg/L. It should be noted that the effluent limit was changed to 3 mg/L TN in 1990. Prior to that time, the limit was 4 mg/L TN in summer and 5 mg/L in winter. The average effluent TSS is 2 mg/L and is relatively stable. Hookers Point has a process loading rate of 1.32 kg NO_x-N/m^2/d (0.27 lb/ft^2/d). The brewery waste may contribute significantly to the background nitrogen removal by synthesis. The plant's overall efficiency in removing nitrogen and SS has been 93 and 99%, respectively.

5.7. Energy Requirement

5.7.1. Coarse Media Beds

Pumping energy can be computed from the following equation (67):

$$\text{kwh/year} = (1,140\,\text{MGD} \times \text{ft of total average head})/\text{wire-to-water efficiency}$$

For a 0.5 MGD (1.89 MLD) plant treating 14 mg/L of NO_3-N, two 10-ft (3.05 m) diameter by 10-ft (3.05 m) deep tanks would be required. Therefore, using 15 ft of total head and a wire-to-water efficiency of 0.60, 14,250 kwh will be required for wastewater pumping.

Backwashing at a rate of 20 gpm/ft^2 (814 Lpm/m^2), once a month for 4 h would require an additional energy consumption of 1,425 kwh/year.

Upflow and downflow operations consume roughly the same amount of energy.

5.7.2. Fine Media Beds

The energy requirement for PBR fine media beds is shown in Fig. 14.16. The assumptions for energy determination are as follows (71):

(a) Influent NO_3-N = 25 mg/L; effluent = 0.5 mg/L
(b) Media size = 2–4 mm
(c) Temperature is 15°C
(d) Methanol feed rate = 3 : 1(CH_3OH : NO_3-N)
(e) Loading rate = 1.7 gpm/ft^2 = 4.15 $m^3/m^2/h$ = 69.2 Lpm/m^2
(f) Depth = 6 ft = 1.83 m
(g) Backwash for 15 min at 25 gpm/ft^2 (1017.5 Lpm/m^2) and 25 ft (7.6 m) TDH once per 2 d for pressure and daily for gravity system.

5.8. Costs

5.8.1. Coarse Media Beds

The construction cost for PBR coarse media beds is determined as follows: for a 0.5 MGD (21.9 L/s) plant treating 14 mg/L NO_3-N, two 10-ft (3.05 m) diameter by 10-ft (3.05 m) deep tanks would be required. Construction costs (1972 Dollars, Utilities Index = 141.94) for such a system was approximately $200,000 (63). To obtain the value in terms of the present 2009

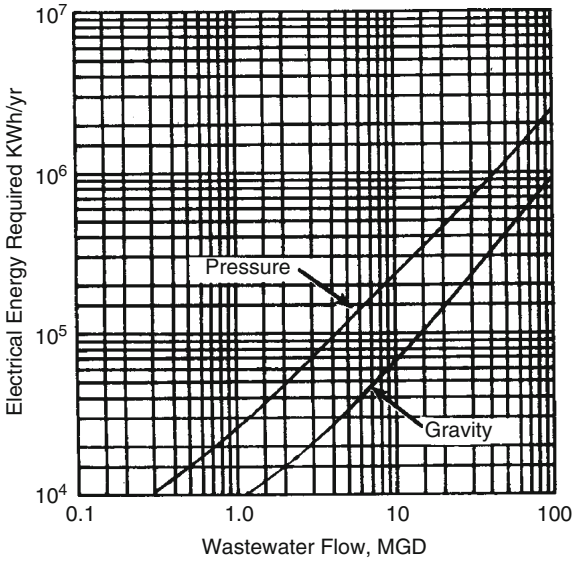

Fig. 14.16. Energy requirements for PBR system (67). (Conversion factor: 1 MGD = 3.785 MLD = 43.8 L/s)

U.S. Dollars, using the Cost Index for Utilities (Appendix), multiply the cost by a factor of 570.38/141.94 = 4.02 (72). Thus, the 2009 construction cost for 0.5 MGD (21.9 L/s) PBR beds would be 200, 000 × 4.02 = U.S.$804, 000.

The cost for chemicals (Methanol) is \$0.03 × 4.02 = \$0.12/1, 000 gal (63, 67, 72). The O & M cost for labor is \$0.03 × 4.02 = \$0.12/1, 000 gal. Thus the total operation and maintenance cost in terms of 2009 U.S. Dollars would be \$0.24 per 1,000 gal treated. Here \$1.00/1,000 gal = \$0.2642/1,000 L = \$0.2642/m^3.

5.8.2. Fine Media Beds

Construction costs (1975 Dollars, Utilities Index = 190.49) for PBR fine media beds are shown in Fig. 14.17 (67). To obtain the values in terms of the present 2009 U.S. Dollars, using the Cost Index for Utilities (Appendix), multiply the costs by a factor of 570.38/190.49 = 2.99 (72).

The operation and maintenance costs for a 0.5 MGD (21.9 L/s) plant treating 14 mg/L NO_3-N is determined as follows: The cost for chemicals (Methanol) is \$0.03 × 4.02 = \$0.12/1, 000 gal (63, 67, 72). The O & M cost for labor (including normal maintenance and daily backwash) is \$0.04 × 4.02 = \$0.16/1, 000 gal. Thus, the total operation and maintenance cost in terms of 2009 U.S. Dollars would be \$0.28 per 1,000 gal treated. Here \$1/1,000 gal = \$0.2642/1,000 L = \$0.2642/m^3.

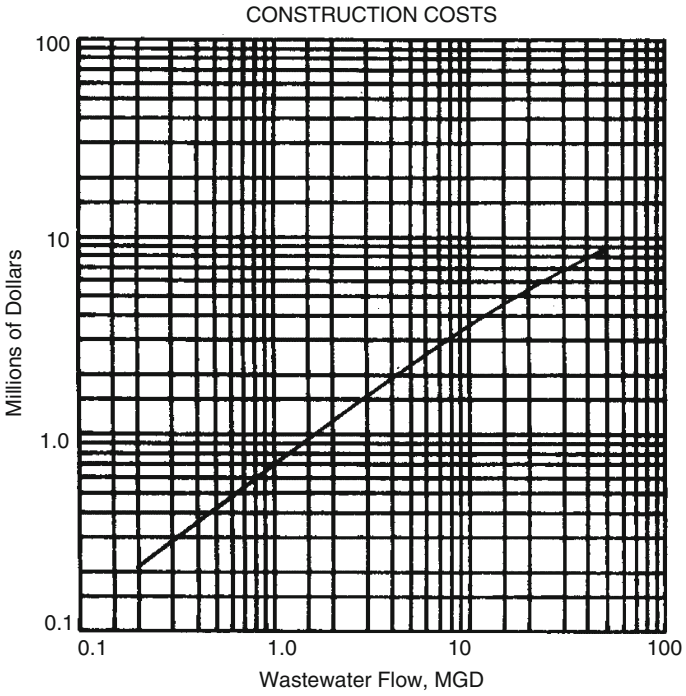

Fig. 14.17. Construction cost for PBR system (67). (Conversion factor: 1 MGD = 3.785 MLD = 43.8 L/s)

6. BIOLOGICAL AERATED FILTER

6.1. BAF Process Description

In the biological aerated filter (BAF), the media are submerged in the reactor, and primary clarified wastewater is introduced at the top of the reactor (26). As noted in an US EPA-sponsored study (73), BAF systems are very similar in both physical appearance and mode of operation to a downflow water filter or tertiary wastewater filter except that:

(a) A coarser, low-density medium is utilized.
(b) Air is diffused upward through the media during operation.

The air is introduced into the media through an air diffusion system located approximately 20–25 cm (8–10 in.) above the filter underdrain system (26, 73). This air is supplied to promote biomass growth in the voids of the packed bed and on the media surface above the air diffusion system. The function of the media below the air diffusion system is to remove SS. As newly grown biomass and influent SS buildup in the reactor, the head loss across the unit increases. The unit is backwashed when a predetermined headloss is reached. The backwashing operation involves a series of air scours and liquid flushes with treated effluent. The intent of this operation is to release SS trapped in the voids of the packed bed and to

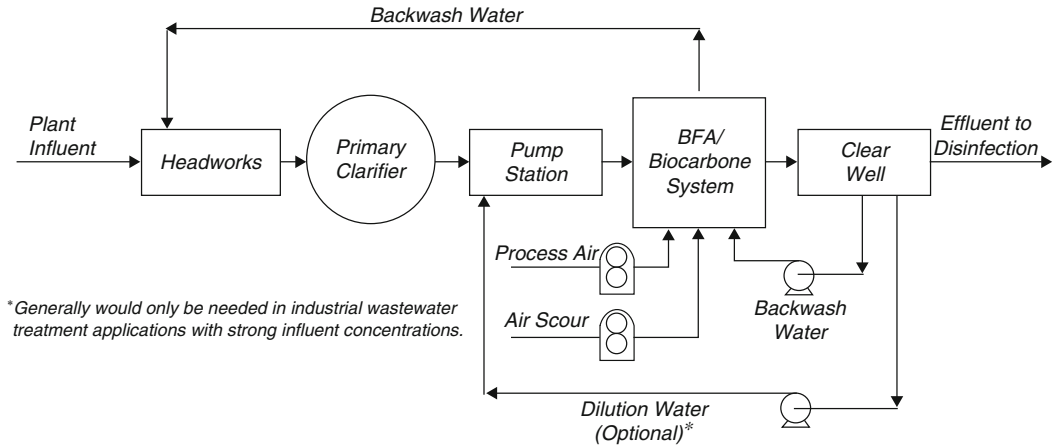

Fig. 14.18. Flow diagram for a biological aerated filter (BAF) system (74).

control the extent of film growth on the media surface (26). The backwash water is either thickened separately or conveyed to primary clarification at the head end of the plant. A common process flow diagram for a complete Biocarbone BAF system is shown in Fig. 14.18 and details of a Bicarbone filter unit is shown in Fig. 14.19. Biocarbone is the trademark name given to Omnium de Traitement et de Valorisation (OTV) commercial embodiment of the process.

When treating primary effluent, the BAF/Biocarbone process can be designed to achieve carbonaceous BOD removal only or carbonaceous BOD removal and nitrification by selecting appropriate loading rates. The process can also be designed to achieve advanced secondary treatment removals of BOD and suspended solids as well as nitrification with either primary or secondary effluent feed (74).

The primary advantage of the BAF is biological treatment and solids separation in the same reactor eliminating the requirement for separate secondary clarification. Consequently, the technology could reduce the space requirements for treatment relative to more conventional technologies such as the activated sludge system (26).

The advantages of the BAF process can be summarized as follows:

(a) Absence of secondary clarifier
(b) Compactness. Good alternative when land availability is low or expensive since the reactor has a compact footprint
(c) Modular design and implementation to suit various flow conditions and effluent quality requirements
(d) Considerable inertia against pollution breakthrough under load variations with peak flows up to three times the average
(e) The rapid startup (relative to activated sludge) allows for adjustment in the number of units in service to match the pollution load arriving at the plant

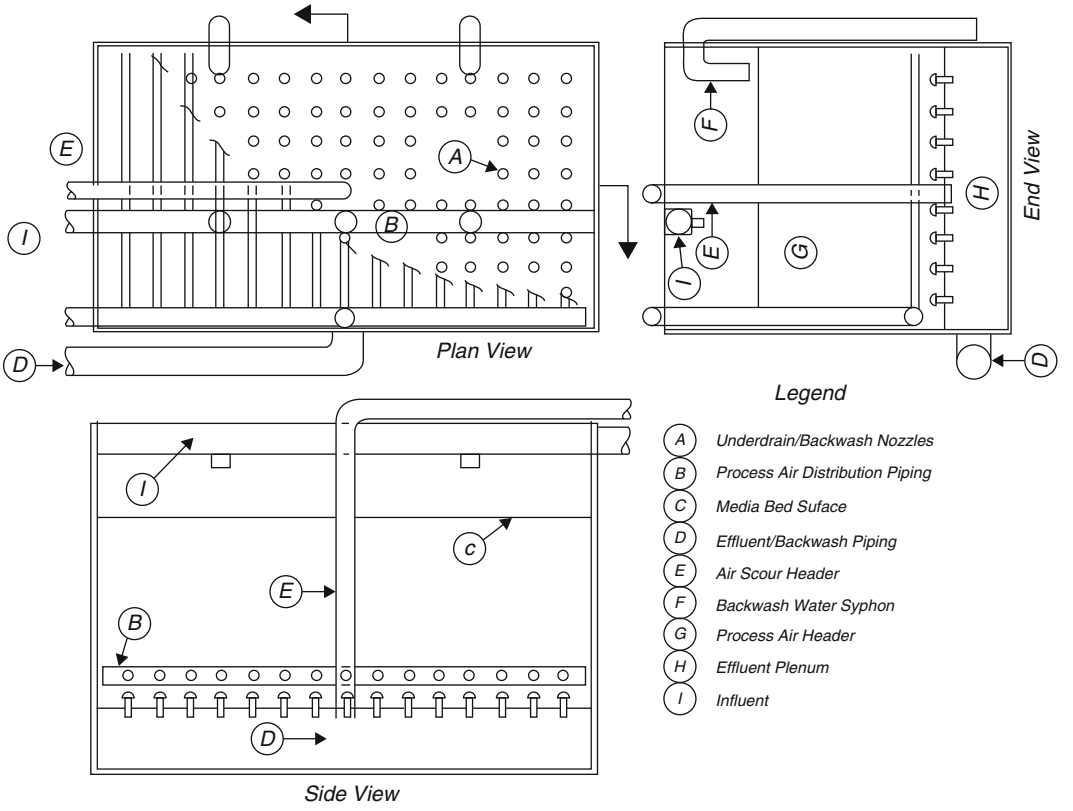

Fig. 14.19. Plan and side views of a BAF/bicarbone unit (74).

6.2. Applications

The first commercial, full-scale BAF system began operation in 1982 in Soissons, France (75). Since that time, a number of systems have been installed in Europe, Japan, and North America (73, 76). As of 1990, there were approximately 30 commercial full-scale Biocarbone BAF systems installed or under construction, designed at wastewater flows of 22 L/s (0.5 MGD) or greater (76). The largest Biocarbone BAF system installed to date is designed to treat approximately 1,056 L/s (24 MGD) (75). Most Biocarbone BAF systems in operation today have been designed for $CBOD_5$ and TSS removal, but the systems can be designed to nitrify primary or secondary effluent.

6.3. BAF Media

The original media employed in the Biocarbone BAF was activated carbon. This material had the desirable characteristics of a porous surface with a high surface-to-volume ratio for enhancing biomass attachment and a low specific gravity to allow for ease of air scouring and backwashing, but it was found too expensive. Subsequently, alternative granular media have

Table 14.6
Recommended BAF media gradation (74)

Media gradation (mm)	Effluent BOD (mg/L)	Effluent TSS (mg/L)
2–4	10	10
3–6	20	20
4–8	30	30

been used for economic reasons. The media in most currently operating BAF systems consist of a kiln-fired clay or shale particle. Biodamine and Biodagene are the names given to two of the media, often used in the Biocarbone BAF (73). Biodamine is an angular-shaped media, whereas Biodagene is more spherical.

The angularity and size range of the media significantly affects the BAF treatment performance and operating requirements. The use of smaller media in the range of 2–4 mm (0.08–0.16 in.), although it offers a superior effluent quality to that of a system with larger sized media, normally requires more frequent backwashing (73). The smaller media have been recommended when nitrification is required (76). Expected effluent quality as a function of media gradation is shown in Table 14.6 (74).

6.4. Process Design and Performance

OTV through years of conducting pilot- and full-scale Biocarbone plant evaluations has developed reliable correlations between applied pollutant and/or hydraulic loading rates and effluent quality or percent pollutant removal (73, 74).

One of these generalized correlations is depicted in Fig. 14.20 for two types of media, activated carbon and biodamjne (vitrified clay particles). Effluent quality from a Biocarbone unit is graphically depicted in Fig. 14.21.

Pilot plant studies by the developer of the Blocarbone BAF system (73) indicate that for a system treating primary effluent wastewater containing a high $CBOD_5$ concentration, nitrification is governed in part by the COD volumetric loading. The volumetric loading is based on the volume occupied by the media (i.e., empty bed volume). The results (Fig. 14.22) indicate that at a COD volumetric loading above 0.2 lb/ft^3/d (3.2 kg/m^3/d), nitrification is substantially reduced because of increased heterotrophic organism growth and associated oxygen consumption. The above loading condition is of concern mainly when primary effluent must be nitrified in conjunction with removing carbonaceous BOD.

Nitrification of secondary effluent, on the other hand, is governed mainly by the TKN loading to a Biocarbone unit. Between nitrogen loadings of 0.010 and 0.037 lb TKN/ft^3/d (0.16 and 0.59 kg/m^3/d), NH_3-N removal decreases at a relatively linear rate, from about 90–84% (Fig. 14.22). Loadings above about 0.037 lb TKN/ft^3/d (0.59 kg/m^3/d) result in substantially reduced NH_3-N removal rates (74).

Based on data from another Biocarbone pilot plant study (76), a COD volumetric load of less than 2.0 kg/m^3/d (0.125 lb/ft^3/d) was required to achieve approximately 90% ammonium oxidation in a single BAF unit. The BAF medium used in the pilot study was metamorphosed shale with a grain size between 3 and 6 mm (0.12–0.24 in.).

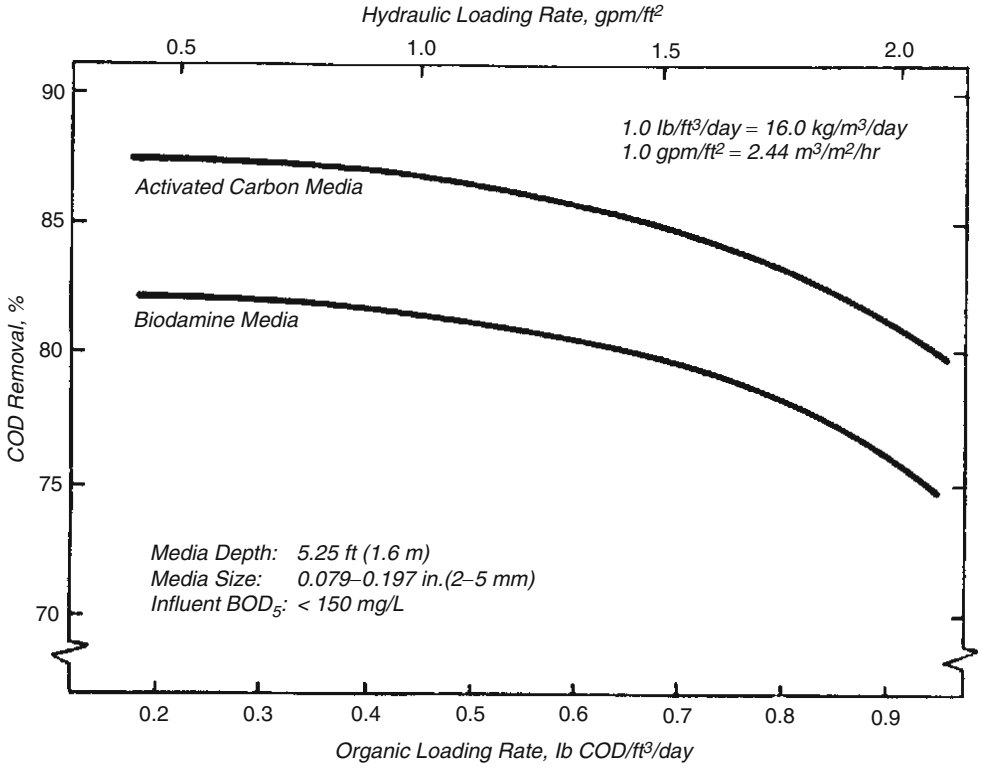

Fig. 14.20. COD removal as a function of BAF influent COD and hydraulic loading rates (74).

Pilot plant studies also provided data on the temperature dependence of NH_3-N oxidation. Based on ammonia-N oxidation in secondary effluent, OTV reported removal rates to approximate the following (74):

(a) At 12°C (54°F) the ammonia-N removal rate is 0.39 kg/m^3/d (0.024 lb/ft^3/d)
(b) At 18°C (64°F) the ammonia-N removal rate is 0.50 kg/m^3/d (0.031 lb/ft^3/d)
(c) At 24°C (75°F) the ammonia-N removal rate is 0.60 kg/m^3/d (0.037 lb/ft^3/d)

According to results from the operation in the United States of a full-scale demonstration Biocarbone BAF plant treating primary municipal wastewater in the mid-1980s (77), the BOD_5 volumetric loading must be limited to approximately 1 kg/m^3/d (0.0624 lb/ft^3/d) to achieve near 90% ammonium oxidation in a single unit. This conclusion is based on operation at temperatures as low as 11°C (52°F) using a vitrified clay medium with an effective size of 3.4 mm (0.13 in.) and a uniformity coefficient between 1.5 and 1.6. Other more recent full-scale Biocarbone BAF plant assessments indicate that to achieve an average effluent ammonia-N concentration of 2.5 mg/L in the treatment of primary effluent, the COD volumetric loading must be limited to approximately 5 kg/m^3/d (0.312 lb/ft^3/d). The volumetric loading rate results indicate that carbonaceous oxidation and nearly complete nitrification of primary

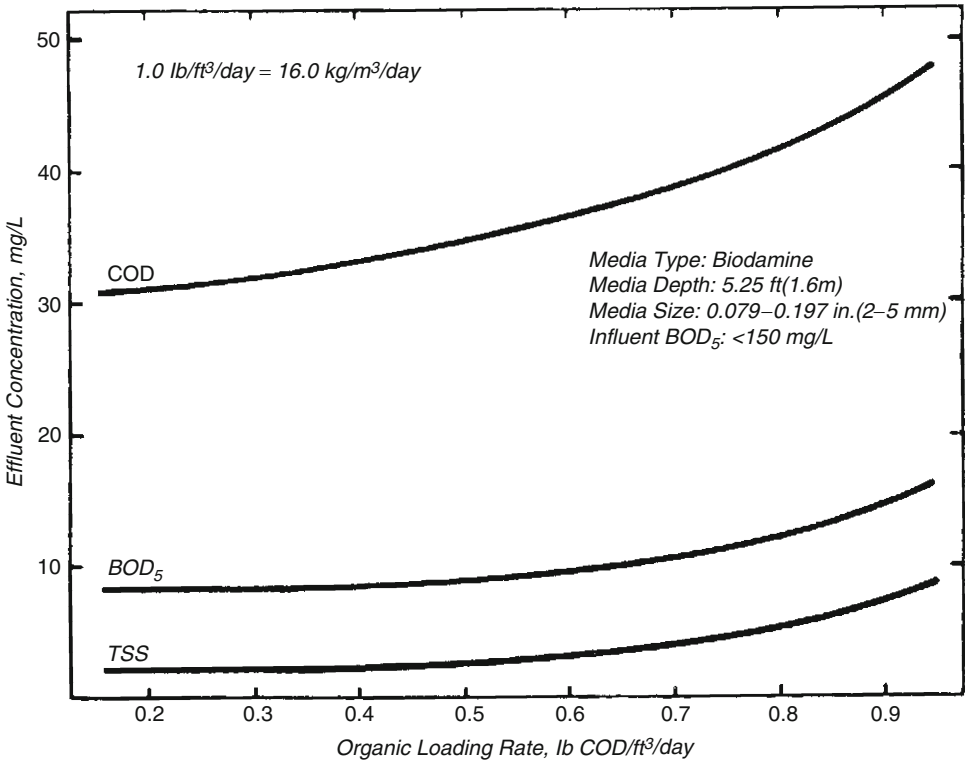

Fig. 14.21. BAF effluent quality as a function of influent COD loading rate (74).

treated wastewater can be achieved in single BAF units at an empty bed hydraulic retention time of approximately 1.5–3.5 h.

BAFs are typically designed to treat municipal wastewaters with low carbonaceous feed concentration, such as that characteristic of secondary effluent. In an US EPA-sponsored, detailed assessment of BAFs (73), information derived from operation of a full-scale BAF unit treating secondary effluent was used to develop a design approach to predict the empty bed hydraulic retention time required to achieve nitrification. At an influent BOD_5 and TSS concentration of approximately 20 mg/L, a hydraulic retention lime of 0.83 h was predicted to be required to reduce the ammonium nitrogen from approximately 21–7 mg/L. These results translate to an ammonium-nitrogen loading of $0.58\,kg/m^3/d$ ($0.036\,lb/ft^3/d$). Other reports indicate that over 90% removal of ammonium nitrogen is achievable at comparable volumetric loading rates at temperatures as low as 13.5°C (56.3°F) (75). Design parameters extracted from various publications (74–87) are listed in Table 14.7.

Although full-scale application of BAFs for municipal wastewater treatment has become widespread in recent years, particularly in Europe (76), the amount of operating and performance information on U.S. installations is limited. The lack at an extensive data base on

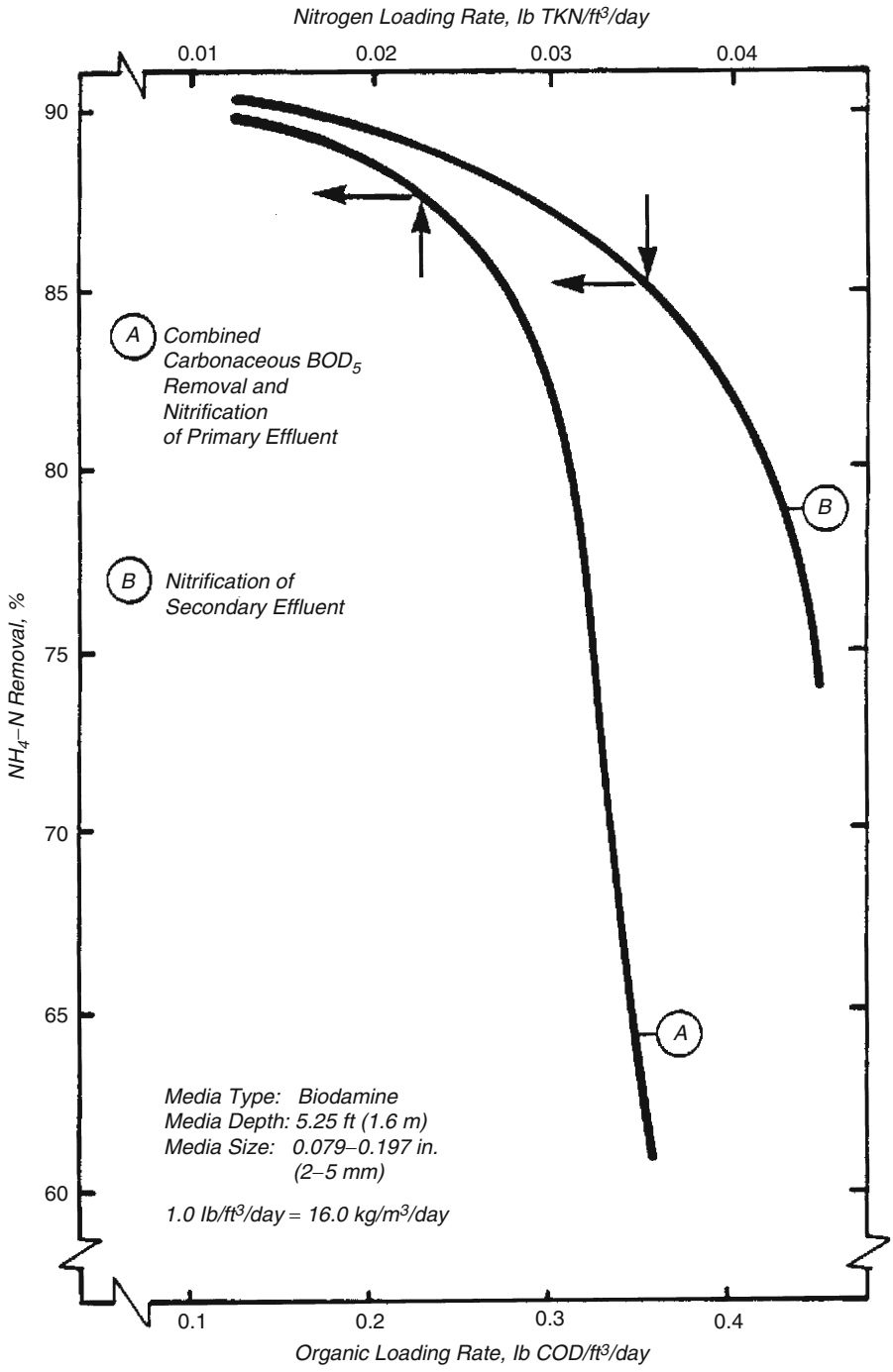

Fig. 14.22. Effect of COD loading on BAF nitrification performance (74).

Table 14.7
Design parameters for biological aerated filter (BAF)

Parameter	Units	Range
Organic loading	kg BOD/m^3/d	3–5
Hydraulic loading	m^3/m^2/d	1–4
Contact time	h	0.5–1
Sludge production	kg SS/kg BOD	0.6–0.9
Bed height	m	2–3
Backwashing	m^3	2.5–3 × filter volume
Backwashing time	min daily	20
Energy consumption	kwh/kg BOD	1.0–1.3

nitrification applications suggests that onsite piloting may be warranted before selecting a technology (26).

6.5. Solids Production

The solids production rate in the BAF/Biocarbone process is a function of, among other factors, the quantities of soluble BOD, nonbiodegradable TSS, NH_3-N, and TKN removed. OTV initially used the historic solids production approximation of 0.7–0.8 lb solids/lb total BOD removed (0.7–0.8 kg solids/kg total BOD removed). A larger data base acquired from both pilot- and full-scale facilities yielded the following two modifications by OTV to their historic solids production value:

Solids production rate (50):

$$= 0.4\,\text{lb/lb soluble } BOD_5 \text{ removed} + 1.0\,\text{lb/lb insoluble } BOD_5 \text{ removed} \quad (2)$$

$$= 0.4\,\text{lb/lb soluble } BOD_5 \text{ removed} + 1.0\,\text{lb/lb TSS removed} \quad (3)$$

$$= 0.4\,\text{kg/kg soluble } BOD_5 \text{ removed} + 1.0\,\text{kg/kg insoluble } BOD_5 \text{ removed} \quad (2a)$$

$$= 0.4\,\text{kg/kg soluble } BOD_5 \text{ removed} + 1.0\,\text{kg/kg TSS removed} \quad (3a)$$

Either of the above predicted models may be used to approximate the net solids production rate.

7. HYBRID BIOLOGICAL-ACTIVATED CARBON SYSTEMS

7.1. General Introduction

While the following processes were developed in laboratory experiments and verified in pilot studies in 1980s, they became popular only recently:

(a) First physicochemical fluidized bed GAC process
(b) First biological fluidized bed GAC process
(c) First physicochemical GAC sequencing batch reactor (SBR)
(d) First biological GAC-SBR
(e) First combined dissolved air flotation (DAF) and GAC process
(f) First DAF-PAC process
(g) First physicochemical PAC-SBR process
(h) First biological PAC-SBR process
(i) First physicochemical PAC-DAF-SBR process
(j) First biological PAC-DAF-SBR process
(k) First ion exchange SBR process
(l) First physicochemical SBR process, and
(m) First regenerable gas phase GAC system.

Because of the importance of the above technologies, many U.S. patents concerning GAC/PAC in combination with SBR, DAF, and precoat filtration were filed by and granted to Wang and his co-workers (88–91)

The biological GAC filtration process was introduced as a competitive process to DAF-GAC process in 1989 (92). Mainstream Bio-Manipulation systems Ltd., adapted both the slow sand filtration and biological GAC filtration processes in 1996 for drinking water production (93). In 2003, the first dual-stage biological GAC filtration plant is the 230-ML/d (230-million liters per day) Ngau Tam Mei Water Works, Hong Kong, China (94). In 2000, the first biological fluidized bed GAC system was built by both Envirogen and US Filter for groundwater decontamination (95).

7.2. Downflow Conventional Biological GAC Systems

7.2.1. Introduction

The granular activated carbon (GAC) adsorption system can remove many adsorbable organics and inorganics, but not nonadsorbable pollutants, such as dimethylnitrosamine, acetone cyanohydrin, butylamine, choline chloride, cyclohexylamine, diethylene glycol, ethylenediamine, triethanolamine, and ethanol. A biological process, on the other hand, can remove biodegradable pollutants and not any nonbiodegradable pollutants. Combination of both processes will solve many traditionally unsolvable environmental pollution control problems.

It has been recognized by researchers and engineers that biological activity plays a major role in the removal of organics by activated carbon. When granular activated carbon is used simultaneously as the filtration and biological growth media in an attached growth biological oxidation–adsorption system, such a combination is called biological GAC adsorption system.

The conventional biological GAC process consists of a fixed bed of granular activated carbon media over which wastewater is applied for aerobic biological and adsorption treatment aiming at the removal of toxic organic substances. Biological slimes form on the GAC media, which assimilate and oxidize substances in the wastewater. The bed is dosed by a distributor system, and the treated wastewater is collected by an underdrain system.

The organic material present in the wastewater is degraded by population of microorganisms attached to the GAC media and partially adsorbed by GAC macropores and micropores. The thickness of the slime layer increases as the microorganisms grow during the bio-oxidation process. The macropores and micropores of GAC are also gradually saturated by the target organic pollutants during adsorption. The microorganisms are also partially responsible for continuous GAC regeneration and prolonged adsorption. Periodically, the GAC bed must be backwashed and regenerated for reuse.

Both downflow pressurized biological GAC system and downflow gravity biological GAC system are technically feasible for water and wastewater treatment as long as oxygen is available for bio-oxidation (96, 97).

7.2.2. Saskatchewan-Canada Biological GAC Filtration Plant for Biological Treatment of Drinking Water

Slow sand filtration (water moves through such filters 10–20 times slower than in rapid sand filters) relies on the formation of a biological layer at the top of the filter. The filter does not become effective until this layer has been formed (92, 93). The American Water Works Association (AWWA) states: "The slow sand filtration process is expected to remove such biological particles as cysts, algae, bacteria, viruses, parasite eggs, nematode eggs, and amorphous organic debris at 100- to 10,000-fold levels when the filter is biologically mature." As effective as sand filtration can be, it is possible to maintain much greater numbers of microorganisms if the support material is GAC instead of sand. It is therefore preferable to use GAC for the removal of dissolved organics (93).

Mainstream Bio-Manipulation Systems Ltd., Canada, has, with the support of the National Research Council, worked on adapting both the slow sand filtration and biological GAC filtration processes. Such treatment systems have been installed at three different sites across Saskatchewan. One site has been in operation since 1996 and removal rates of turbidity, dissolved organic carbon, and color have been good for both the sand filter and the biological GAC filter. Both have provided high-quality household water with no color or odor (removal rates of turbidity, dissolved organic carbon, and color are consistently above 50%). For drinking water purposes, the water is polished by a reverse osmosis unit. All of the household water was hauled before installation of the biological treatment system. Based on successes like this one, it is anticipated that biological treatment will become one of the most common future treatment tools for dealing with surface waters on the Canadian prairie (93).

7.2.3. Ngau Tam Mei Water Works, Hong Kong, China

In 1994, facing projected shortfalls of potable water for the North Western New Territories of Hong Kong, the water supplies department initiated new facilities for treatment,

conveyance, and storage of water from its major supply, the Dongjiang River in Guangdong Province, People's Republic of China, via the Western Aqueduct.

In 2000, the Ngau Tam Mei water treatment works was commissioned, officially opening on December 2. It is the first water treatment plant worldwide to use dual-stage biological filtration with granular activated carbon (GAC) to remove ammonia, replacing break-point chlorination (94). The HK$ 1.8 billion (US$ 227 million) project treats river raw water, which is contaminated by wastewater. The plant was designed with an initial capacity of 230 ML/d, expandable to 450 ML/d. Here 1 ML/d = 1 MLD = 1 million liters per day.

The innovative plant was able to meet or surpass the required water quality goals by employing the following treatment units:

(a) Four preozone contact tanks with a design detention time of 5 min
(b) Twelve triple-deck sedimentation basins with a designed surface loading rate of 1.3 m/h
(c) Intermediate ozone contact tanks with a design retention time of 15 min for achieving 1-log inactivation of Cryptosporidium
(d) Twelve first-stage GAC (1.5-m depth) filters with minimum filters run time of 24 h and filtration rate of 12 m/h, followed by 12 s-stage GAC (1.8-m depth) filters with a filtration rate of 8 m/h, and
(e) Ozone peak dosage of 5 mg/L, ozone production rate of 1,150 kg/d, and ozone concentration of 7.5%.

The plant has been designed such that it is able to reduce O & M cost by:

(a) Generating high-quality oxygen on site, eliminating more costly truck-delivered liquid oxygen
(b) Using dual-stage GAC filters to remove ammonia, eliminating break-point chlorination
(c) Providing flexibility for operating in direct-filtration mode during periods of acceptable raw water quality to reduce coagulant chemical doses and sludge production, and
(d) Reducing labor cost and improving plant management through a supervisory control and data acquisition (SCADA) system (94)

The three special advanced features of this largest biological GAC filtration plant include: (94)

(a) *Dual-stage biological GAC filtration*. A first-of-its-kind application in drinking water treatment. First-stage filters remove turbidity, biodegradable organic carbon, and taste- and odor-causing compounds. Second-stage filters remove ammonia, eliminating break-point chlorination and associated high chlorine doses. Results since commissioning show complete removal of ammonia (effluent concentration < 0.02 mg/L)
(b) *Ozonation for primary disinfection*. This inactivates Giardia and Cryptospordium, and reduces chlorine usage, helping to eliminate formation of chlorinated byproducts (THMs) and enhancing downstream biological filtration by oxygenating water and increasing formation of biodegradable organic carbon.
(c) *Ozonation for manganese removal*. Process uses preozonation for oxidation of reduced manganese to its insoluble form (manganese dioxide) for subsequent removal by coagulation and settling, followed by intermediate ozonation, which oxidizes remaining manganese in the settled water to permanganate for subsequent catalytic removal by first-stage GAC filters.

7.3. Upflow Fluidized Bed Biological GAC System

Upflow fluidized bed biological GAC system (FBB-GAC) has less clogging problem than the two downflow biological GAC systems introduced previously. Accordingly, the downflow

biological GAC filtration process is mainly used for potable water treatment, while the upflow fluidized bed biological GAC system may be used for both water and wastewater treatment (92, 98). Many researchers are studying the upflow fluidized bed biological GAC systems (95, 98–100). The first fluidized bed biological GAC system was designed and built in 2000 by Envirogen and US Filter for groundwater decontamination (95).

The FBB-GAC system (Hydroxyl Systems' Fluidized Bed Bioreactor) shown in Fig. 14.23 can be used in aerobic, anoxic, or anaerobic conditions, and can accommodate a variety of granular media (101). When adsorbent media, such as granular activated carbon (GAC), is used, the FBB combines the benefits of adsorption and bio-oxidation. Contaminants are adsorbed onto the media surface and oxidized by the biofilm, which is formed on the GAC surface. Unlike other biological treatment systems, the requirement for operator attention is minimal and unattended operation is practical. One of the most outstanding features of the FBB-GAC is that treatment detention times are typically minutes rather than hours.

The FBB-GAC system is supplied either as a single skid module of shippable height, incorporating a low profile reactor, or as a two-piece unit with a detachable tall cylindrical reactor. The system is used for aerobic, anoxic, or anaerobic treatment of waterborne biodegradable matter, particularly adsorbable contaminants in low mg/L concentrations. Typical applications include treatment of groundwater contaminated with BTEX and as a complement to advanced oxidation technologies for complete mineralization of biorefractory contaminants. As an anaerobic reactor, the FBB-GAC system can be used to treat high-strength wastewaters. Typical treated contaminants include BTEX, glycol, MTBE, soluble Oil & Grease and organic solvents.

The FBB-GAC system has the following special features (101):

(a) Fast bio-oxidation
(b) Fully automated with PLC control

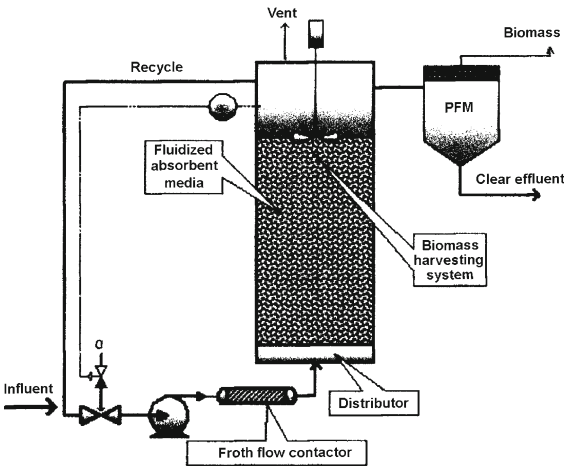

Fig. 14.23. Fluidized bed biological (FBB)-GAC system (101).

(c) Weatherproof container (optional)
(d) No plugging or sludge bulking
(e) No post-clarification required
(f) Very compact and portable
(g) Unattended operation, and
(h) No off-gas

An extremely high concentration of biomass develops in the reactor because of the huge surface area provided by the media, abundant oxygen, and optimized mass transfer conditions. Excess biomass is periodically and automatically removed by extracting media, shearing the biomass and returning the cleaned biomass to the reactor. The effluent from the FBB-GAC is typically very low in suspended solids, allowing effluent discharge without further treatment (101).

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APPENDIX

U.S. Army Corps of Engineers Civil Works Construction Yearly Average Cost Index for Utilities (72)

Year	Index	Year	Index
1967	100	1989	383.14
1968	104.83	1990	386.75
1969	112.17	1991	392.35
1970	119.75	1992	399.07
1971	131.73	1993	410.63
1972	141.94	1994	424.91
1973	149.36	1995	439.72
1974	170.45	1996	445.58
1975	190.49	1997	454.99
1976	202.61	1998	459.40
1977	215.84	1999	460.16
1978	235.78	2000	468.05
1979	257.20	2001	472.18
1980	277.60	2002	484.41
1981	302.25	2003	495.72
1982	320.13	2004	506.13
1983	330.82	2005	516.75
1984	341.06	2006	528.12
1985	346.12	2007	539.74
1986	347.33	2008	552.16
1987	353.35	2009	570.38
1988	369.45		