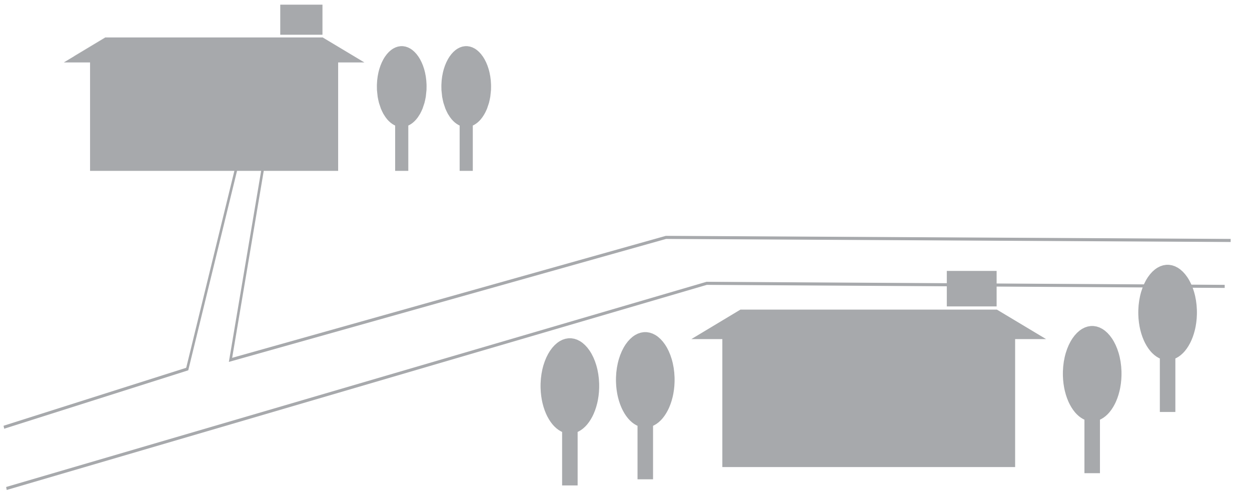
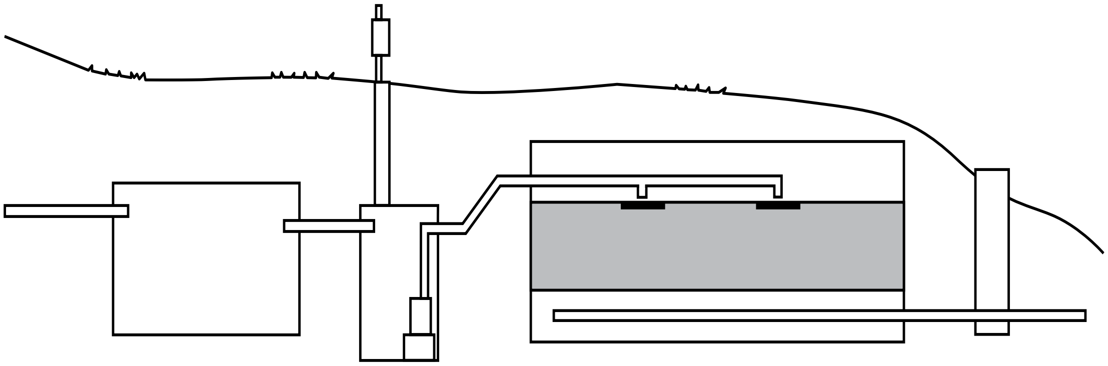
Bulletin 876

Sand and Media Bioreactors for Wastewater Treatment

for Ohio Communities





THE OHIO STATE UNIVERSITY
EXTENSION

Karen Mancl, Professor
Department of Food, Agricultural, and Biological Engineering
The Ohio State University

Jing Tao, Graduate Research Associate
Environmental Science Graduate Program
The Ohio State University

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Keith L. Smith, Ph.D., Associate Vice President for Agricultural Administration and Director, Ohio State University Extension

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Introduction

Small communities and rural businesses are looking for different ways to treat wastewater. Strict stream discharge requirements are reducing the number of treatment options. Increasing construction costs make extensive sewer networks impractical. Large fluctuations in flow in recreational communities and some businesses upset the operation of traditional treatment systems. Therefore, communities and regulators are looking for new options.

One well-established treatment option is a sand bioreactor, also known as a sand filter. Beds of sand have been used to treat wastewater in communities since the late 1880s (Mancl and Peeples 1991). Dozens of communities in Massachusetts operated sand filters for wastewater treatment for more than 40 years. The systems were eventually abandoned, but not because they didn't work; the communities grew, so the land was converted to new uses.

Sand bioreactor technology was forgotten for a good part of the twentieth century. Activated sludge treatment technology was developed, and engineering programs around the nation taught students about these mechanical systems. They were smaller in size, but they were complicated and required more energy and skilled labor to build and operate.

During the 1980s, researchers began looking for treatment systems that produced excellent effluent quality with lower energy and labor requirements. Sand bioreactors were "rediscovered." Advances in the technology both reduced the system size and increased the effluent quality. New strategies of wastewater applications, like dosing and recirculation, reduced the size of sand bioreactors. New artificial media have been studied to make bioreactors easier to construct.

This bulletin is intended for designers and regulators of wastewater treatment systems. It will present basic sand bioreactor design along with new advances in technologies.

How do sand and media bioreactors work?

In almost all wastewater treatment systems, naturally occurring microbes grow and consume the pollutants in wastewater. Groups of microbes naturally colonize surfaces, where it is easy for them to stay moist and have access to air and food. These microbes will grow on all types of media, like sand, cloth, and plastic. The same process occurs on teeth, where biofilms grow in a moist environment with access to food and air. While brushing one's teeth removes the biofilm, the biofilm quickly grows again. This process also occurs in the soil under septic systems. As long as the soil is well structured, the microbes can grow on the aggregate surfaces. If the soil isn't saturated, the empty soil pores provide the necessary air for the microbes.

Figure 1 illustrates this process. The microorganisms draw nutrients, organic matter, and oxygen from the wastewater and the air that pass through the media bed. The media also traps most suspended solids. Sand and media bioreactor effluent is typically very clear with low biochemical oxygen demand (BOD_5) and ammonia levels.

Care must be taken in applying wastewater to sand and media bioreactors. If saturated with water, the microbes get deprived of oxygen and the reactor begins to clog. If continually overloaded, the media tends to clog. In this way, sand and media bioreactors are fail-safe, requiring the owner or operator to take corrective action. A malfunctioning sand or media bioreactor will back up rather than release poorly treated effluent to a receiving stream.

These bioreactors also differ from those that receive secondary treated effluents. Sometimes a filter is used after an aerobic treatment plant to physically filter the wastewater to remove excess suspended solids and to "polish" the effluent. A filter used for effluent polishing serves a different function than a sand or media bioreactor, has different design requirements, and is not covered in this document.

Sand and media bioreactors respond well to gradual increases in wastewater loading. Therefore, they are very appropriate for new developments with a gradual build-out rate. These bioreactors also tolerate fluctuations in flow, especially changes from a negligible flow to very high flows. In this way, they are appropriate for seasonal use and recreational areas. Research shows that sand bioreactors receiving no wastewater for 4–6 months can immediately treat wastewater when put back into service (Kang et al. 2007a; Tao et al. 2011).

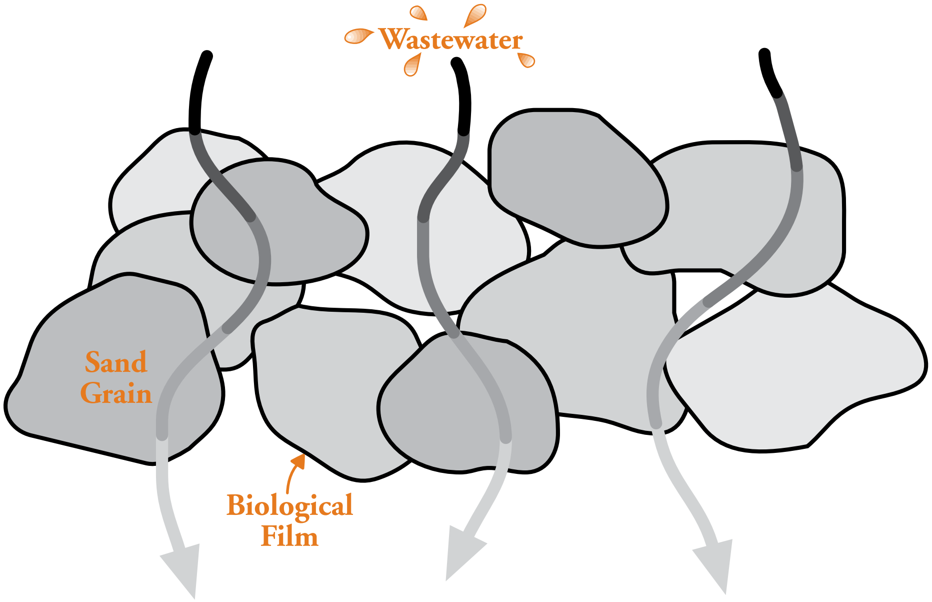


Figure 1. Microorganism growth on sand grains in a sand bioreactor system.

How much sand is needed to treat wastewater?

Most of the treatment in a sand bioreactor occurs in the top 9–12 inches. Deeper filters produce a more consistent quality effluent, but after 24 inches, research shows no significant treatment improvement is achieved with added depth (Widrig et al. 1996, US EPA 1980). Additionally, air penetration into a deep media bed is more difficult, so deeper bioreactors are more likely to clog. Therefore, a depth of about 24 inches is appropriate for most domestic wastewater.

What type of sand should be used?

Media characteristics are the critical design criteria for bioreactors. The effective surface area of the media determines the treatment efficiency. For sand, the most important feature is not the grains, but rather the pores the sand creates. The treatment of wastewater occurs in the pores, where suspended solids are trapped, microorganisms grow, and air and water flow. Bioreactor clogging is usually the result of using media that 1) has too many fine particles, 2) dissolves over time, and/or 3) can be easily crushed or flattened in shape. See Table 1 for basic sand bioreactor design criteria.

For sand bioreactors, the ideal media is hard and nearly spherical in shape. Quartz sand is often used because it is inexpensive and readily available. Garnet sand, mineral tailings, expanded clays, and other materials have all been successfully used. Never use limestone sand in sand bioreactors, because the sand will begin to dissolve with the continued application of wastewater.

The size distribution of the sand is reported as the effective size and the uniformity coefficient. Sand effective size and uniformity coefficient affect bioreactor performance. The determination of them with sieve analysis is described in Appendix 1. BOD_5 and ammonia removal are a function of effective size. Ideal sands for intermittent bioreactors are a medium to coarse sand with an effective size between 0.3 mm and 1.0 mm.

Sand uniformity is an important factor in design. Uniformity controls the size of the pore spaces. If all of the sand is exactly the same size, the pores will also be the same size. If small sand particles are mixed with large sand particles, the small ones will fill the spaces between the large ones thus creating a range of pore sizes. If the sand is made up of a wide range of sizes, the pores will be very small and will clog easily.

Sand uniformity is gauged by its uniformity coefficient. If the uniformity coefficient is 1, all of the sand is the same size. The higher the coefficient number, the greater the range of sand grain sizes. The ideal sand for bioreactors has a uniformity coefficient of less than 4. Sands with low uniformity coefficients do not occur naturally in Ohio and must be processed to clean out excess fine material, making them more expensive.

Table 1. Basic sand criteria for non-limestone sand for use in single-pass bioreactors.

Discharge Requirement	*Effective Size (mm)*	*Uniformity Coefficient*
Very low effluent BOD_5 and ammonia (for stream discharge)	0.3–0.5	less than 4
Low effluent BOD_5 (for irrigation on public access sites)	0.5–1.0	less than 4

Basic sand criteria for non-limestone sand for use in recirculating bioreactors.

Discharge Requirement	*Effective Size (mm)*	*Uniformity Coefficient*
Low effluent BOD_5	0.5–1.5	less than 4

How much area is needed for a sand bioreactor?

The size of a sand bioreactor is easy to determine. Bioreactors treating domestic sewage are designed at 1.0 gal/ft^2/day. Therefore, if the design loading is 500 gal/day, the sand bioreactor would be 500 square feet. The shape of the bioreactor can be adjusted to meet the needs of the site, and multiple smaller bioreactors can be constructed to accommodate all of the wastewater. For easy construction, sand bioreactors are usually 10 feet wide and up to 50 feet long, with multiple units constructed on a site.

With recirculation, bioreactors can be much smaller. For domestic wastewater, recirculating sand bioreactors can operate on a forward flow of 5 gal/ft^2/day. For example, if the design flow is 500 gal/day, a recirculating sand bioreactor would be 100 square feet.

How should wastewater be applied?

Careful wastewater application is required. Never use large perforated pipes—like those used in leach fields—to load wastewater onto a sand bioreactor. Discharge from large perforated pipes is not uniform and therefore results in some areas of the bioreactor being overloaded and others receiving no effluent. Also, continuous application is not recommended. Since the microbes living in the biofilm must have oxygen, continuous gravity loading runs the risk of saturating the reactor and clogging the sand.

Researchers discovered in the 1950s that dosing has an important impact on the amount of wastewater that can be treated, as well as the quality of the effluent. One dose per day was studied (DeS Furman et al. 1955) as shown in Figure 2a; it works well to distribute and treat the wastewater. However, by dividing the wastewater into two smaller doses and spacing the doses out during the day, the effluent quality improves and more wastewater can be treated in the same area.

Research at The Ohio State University also found that applying multiple doses per day reduced clogging in the sand bioreactor (Figure 2b). While none of the experimental bioreactors completely clogged, with a single dose per day, the sand was 80% clogged while the sand receiving 12 doses per day was only 30% clogged.

Applying multiple doses per day is the recommended dosing strategy. Wastewater flowing through the media tends to flow over the surface as a film of water. A smaller dose results in a thinner film and better contact between the wastewater and the microbes treating it. Figure 3 illustrates the impact of dosing on the flow of wastewater through a sand filter.

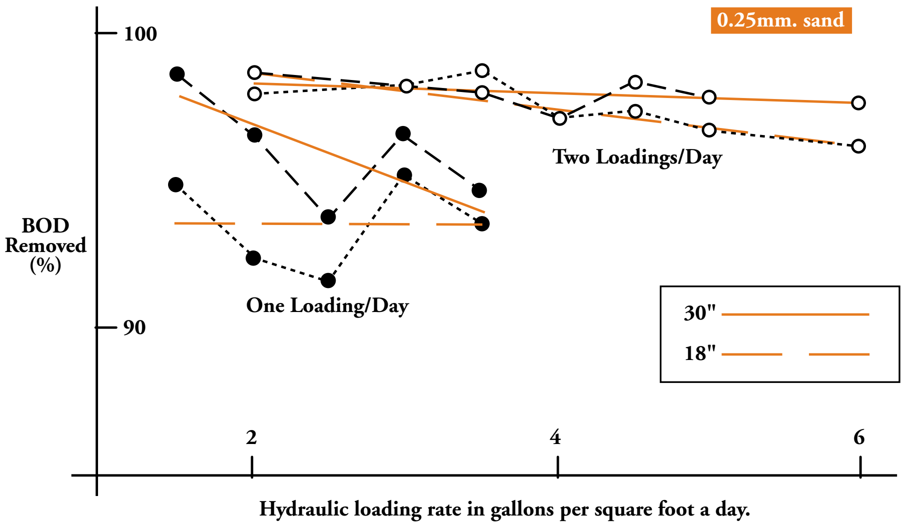


Figure 2a. BOD removal by 18-inch deep and 30-inch deep sand bioreactors under 1 and 2 loadings per day. (Source: DeS Furman et al. 1955)

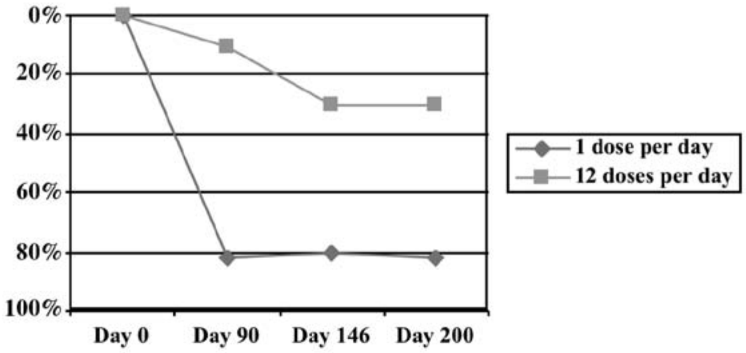


Figure 2b. Clogging in sand bioreactors that treat cheese-processing wastewater. Clogging is measured as the percentage of water discharged from a single dose in 90 minutes. (Source: Xi et al. 2005)

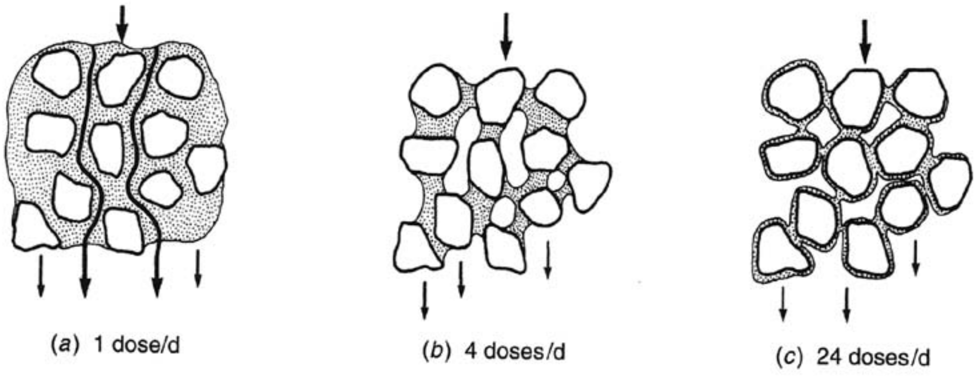


Figure 3. The effect of dosing frequency on the flow of wastewater through sand bioreactors. (Source: Crites and Tchobanoglous 1998)

How many doses are needed?

For some small systems (less than 1,000 gpd) the pressure dosing systems used in mound systems is appropriate. Ohio State University Extension Bulletin 829, *Mound System: Pressure Distribution of Wastewater Design and Construction in Ohio*, explains how to design a small-pressure distribution system. A submersible effluent pump controlled by float switches in a dosing chamber can be used to deliver the accumulated wastewater to the bioreactor surface in small doses. These systems are usually designed to apply from 3–5 doses per day.

For larger systems and systems with large fluctuations in flow, a time-dosed system may be more appropriate. In these systems, a timer in a control panel turns the pump on and off. Small, frequent doses result in a cleaner effluent, and the dosing tank can accumulate wastewater during high flows for distribution during low flow periods. For systems only used during the day, a timer can help apply wastewater to the bioreactor through the night. High weekend flow is another application. With time-dosing, wastewater can be applied throughout the week when flows are low.

Dosed sand bioreactors should be loaded at 1 gal/ft^2/day. With multiple dosing each day, systems of this size can handle occasional high loads without a problem. In lab studies at The Ohio State University (Kang et al. 2007), sand bioreactors were loaded at 6.5 gal/ft^2/day for up to 2 weeks with no increase in effluent pollutant levels and no evidence of clogging.

What if electricity is not available?

In some areas of Ohio, it is not practical to use a pump for dosing a sand bioreactor. In these areas, tipping pans can be used to distribute wastewater over the sand surface. In this approach, wastewater flows under the force of gravity into a pan that rests like a teeter-totter. When one side of the pan fills with wastewater, the weight causes the pan to tip, dosing half of the bioreactor. The empty pan fills again until it tips, discharging wastewater to the other half. A corrugated, perforated tray distributes the wastewater over the bioreactor surface. Figure 4 illustrates a tipping pan used in a bioreactor system.

Figure 4. A tipping pan can be used for dosing wastewater onto bioreactor surfaces.

What are the approaches to applying wastewater?

Intermittent (single-pass) bioreactors receive small wastewater doses that flow by gravity once through the media. Figure 5 illustrates an intermittent bioreactor system. This system consists of a septic tank for pretreatment to remove large solids. A dosing tank accumulates the untreated wastewater, and the tank is equipped with a pump and the controls to dose the wastewater onto the top of a bioreactor. Once treated, the wastewater discharges into an irrigation system. With an NPDES permit, the wastewater can be safely discharged to a receiving stream. If spray-irrigated on public access land or discharged to a stream, disinfection is needed to kill any remaining pathogens.

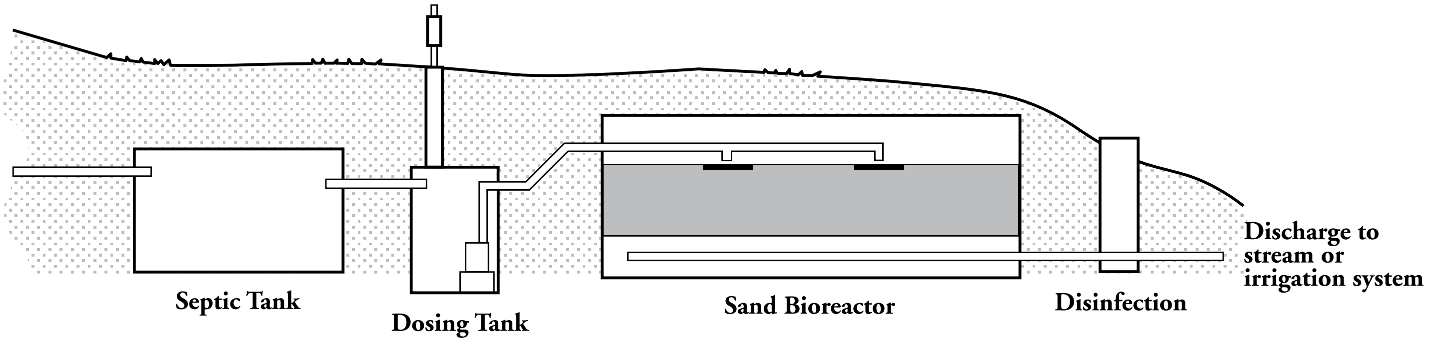


Figure 5. An intermittent (single-pass) bioreactor system.

Cattaragus, New York—a community of 200 homes—treats all of its wastewater through 4 intermittent sand bioreactors. The wastewater is pretreated in one of 4 parallel, 2,500-gallon septic tanks and is applied in 3 to 4 doses per day to a 36-inch deep bed of sand at a dry weather application rate of 1.5 gal/ft^2/day and a wet weather application rate of 6.25 gal/ft^2/day. After UV disinfection, effluent with an average BOD$_5$ of 7 mg/l is discharged to a stream.

Recirculation is a strategy to make a bioreactor even smaller. One way to think of recirculation is it, in effect, makes the bioreactor deeper. By passing the same wastewater through a 2-foot deep bioreactor up to 5 times, the wastewater is exposed to as much as 10 feet in depth of active biofilm. Recirculating wastewater several times through a bioreactor requires four components: a bioreactor, a recirculation pump with a timer, a recirculation tank, and a control valve (Figure 6).

In a recirculation system, wastewater flows from a septic tank into a recirculation tank, where it is mixed with treated wastewater. A timer activates the pump and doses the bioreactor on a predetermined schedule. The tank is big enough to hold 1 part incoming wastewater and 4 parts treated wastewater. When full, the valve closes to discharge about one-fifth of the wastewater from the recirculation tank, making room for the untreated wastewater entering the tank. A simple float valve is usually used to control recirculation in the tank.

In a recirculation system, up to 5 gal/ft^2/day of wastewater are treated with the bioreactor and discharged. However, due to recirculation with treated wastewater, in effect, 25 gallons of liquid may be applied to the filter each day. Mixing treated and untreated wastewater has its advantages. By mixing partially treated, nitrate-containing wastewater with full-strength, anaerobic septic tank effluent, some denitrification can occur to achieve nitrogen removal. Denitrification rates of up to 50% have been achieved with recirculating bioreactors. Denitrification rates increase at higher temperatures.

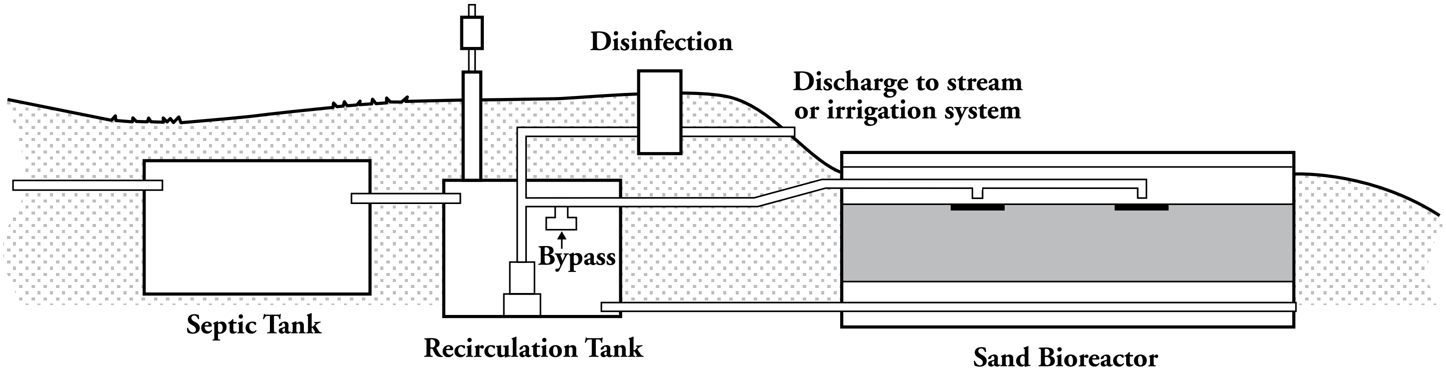


Figure 6. A recirculating bioreactor system.

Oriskany Falls, New York—a community of 900 homes—treats all of its wastewater through 4 recirculating sand bioreactors. The wastewater is pretreated in a septic tank. The septic tank effluent and 33% of the sand filter effluent are mixed in a recirculation tank and applied in 12 doses per day at 10 minutes per dose. The sand beds are 36 inches deep with an application rate of 4 gal/ft^2/day. After UV disinfection, effluent with average BOD$_5$ of 2 mg/l and ammonia ranging from 1.1 to 2.0 mg/l is discharged to a stream.

Can bioreactors be constructed of materials other than sand?

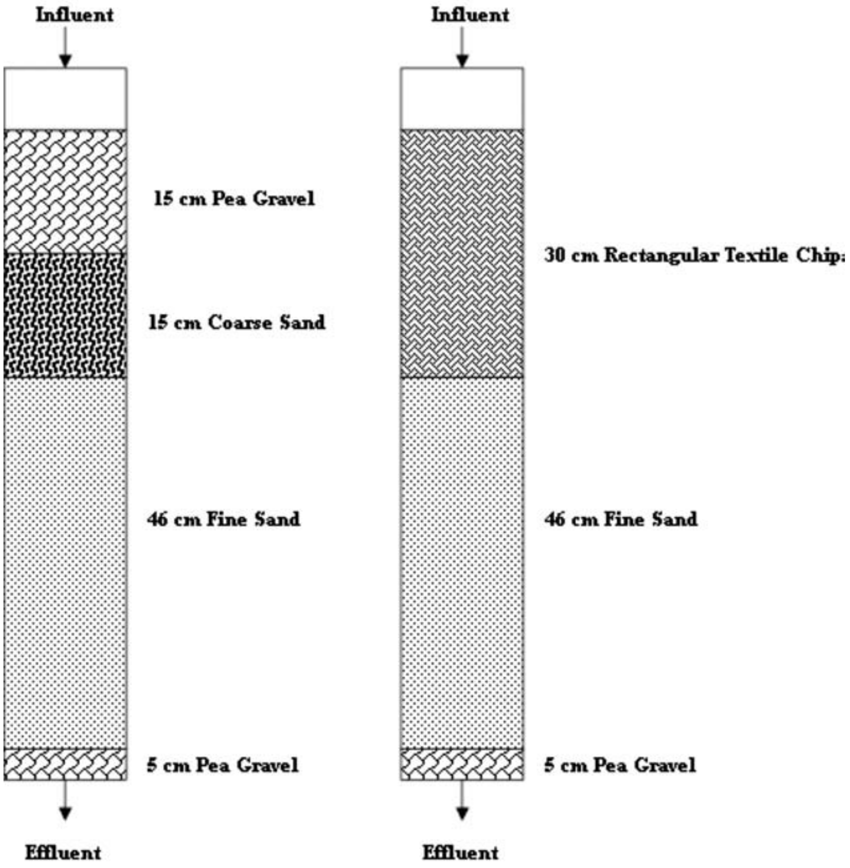
Various materials can be used as media for bioreactors. Microbes will naturally colonize surfaces that are open to the flow of air and wastewater. Therefore, any material used should have a good balance of surfaces and interconnected pore spaces, and it should have the ability to maintain that structure over time. Materials that can pack down or decompose may work well at first, but they may cause maintenance problems in the future.

Peat (Figure 7) and textile are two types of bioreactor media developed during the last 15 years. Peat is partially decomposed organic material with a high-water-holding capacity, large surface area, and chemical properties that make it very effective in treating wastewater. Unsterilized peat is also home to a number of different microorganisms including bacteria, fungi, and tiny plants. Textile bioreactor media is non-woven textile fabrics that have large, effective surface areas; these fabrics permit a high loading rate. This type of media can be cut into squares and placed into a container or hung as curtains in a container.

Some other natural materials such as shale, cinders, and activated carbon can also be used as bioreactor media. Manufactured media include cubic foam, hard plastic fragments, crushed glass, and tire chips.

Box 1 Layered bioreactors

OSU research shows that layers of different media are effective in treating wastewater in special situations. A combination system of 1 foot of textile and 1.5 foot of sand obtained excellent performance in treating high-strength, high-grease content wastewater such as slaughterhouse wastewater (Figure 8b). For treating sanitary sewer overflows that have extremely high flows of low-strength wastewater only a few times a year, three-layer bioreactors were found to be effective (Figure 8a). The layers were 1.5 foot of fine sand, 0.5 foot of coarse sand, and 0.5 foot of pea gravel (Tao et al. 2011).



Figures 8a (left) and 8b (right). Bioreactors used in research at The Ohio State University for the treatment of high-strength, high-grease content wastewater and sanitary sewer overflows.

Peat

Fabric Chips

Cubic Foam

Figure 7. Examples of materials used in fixed-media bioreactors. (Source: Fabric chips, www.winnsystems.com/technical.html; Cubic foam, www.waterloo-biofilter.com)

What does a bioreactor look like on-site?

The appearance of a wastewater treatment system is an important consideration. Sand and media bioreactors are barely noticeable in the landscape. Sand bioreactors are constructed of layers of sand and gravel, making them very stable and safe in lawns and recreational areas. Most bioreactors are buried under the lawn. Often, recirculating bioreactors—or systems constructed with artificial media—have covers for easy access for maintenance. In some environments—such as in big cities or in extremely cold regions—bioreactors are enclosed in buildings.

A buried bioreactor is protected from extreme fluctuations in temperature and hidden from view. The final depth of a fixed-media bioreactor ranges from 4–5 feet, to accommodate the 24 inches of media depth, the supporting gravel and drainage system, the surface distribution system in a gravel cap, and at least a 6-inch layer of insulating soil. Therefore, it is common for a buried bioreactor to be constructed in a shallow excavation and to be mounded above the ground surface (Figure 9). Observation ports are used to determine the onset of ponding. Valve boxes at the ends of distribution pipes provide access to flush pipes, and to check the system pressure when maintaining a bioreactor.

Figure 9. A buried sand bioreactor in Anchorage, Alaska.

A roof protects a covered bioreactor from precipitation and extreme fluctuations in temperature. The shade provided by a roof also eliminates weed growth on the sand surface. However, roofs add to the construction cost and must be constructed with easy access, wind and snow loads, durability, and appearance in mind.

Roof designs vary greatly and must insulate the bioreactor, allow for easy access for maintenance, and please the eye esthetically. The most common roof is lifted off as a single piece or in sections as necessary. Some designs used on bioreactors include a sloped, fixed roof built on posts about two feet above the system surface. Roofs of this type allow an operator to reach under the roof edge to make observations and to access the bioreactor to perform necessary maintenance. Hinges can be placed along one edge of a flat or mono-sloped roof so that the roof can be propped up almost like a car hood. Roofs are made of a variety of materials ranging from small roof trusses with sheathing and shingles to match the nearby buildings, to 2×4 frames with exterior plywood and roofing paper. Corrugated metal and fiberglass have also been used for roofs (Figure 10).

Figure 10. Examples of covers used for bioreactors.

How is a fixed-media bioreactor designed?

The following is one example of the seven-step design of an intermittent, buried sand bioreactor. The design of a recirculating bioreactor is in Appendix II at the back of this publication.

Design Example I: Intermittent, Buried Sand Bioreactor

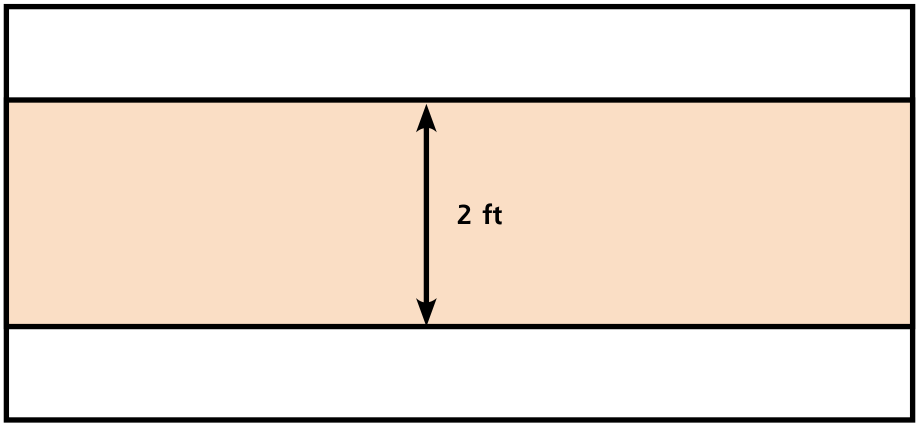
A three-bedroom home has a failing septic system. Because of very shallow soils to compacted, glacial till, an intermittent sand bioreactor is proposed. The design flow is based on 120 gal/day/bdrm.

3 bedrooms * 120 gal/day/bdrm = 360 gal/day

Step 1. Select the appropriate media. Find a local aggregate company that provides non-limestone sand with a uniformity coefficient of less than 4 and an effective size of between 0.5–1.0 mm. In Ohio, check with the Ohio Aggregates and Industrial Mineral Association (**oaima.org**). Request a sieve analysis of the sand to keep on file. A step-by-step sand analysis procedure is described in Appendix 1.

Step 1: For this system, a local aggregate company will provide non-limestone sand with an effective size of 0.9 mm and a uniformity coefficient of 3.5 at a reasonable cost.

Step 2. Determine the media depth. The recommended sand depth for a bioreactor of this kind is 2 feet.



Step 2: For this system, the sand depth is 2 feet.

Step 3. Determine the area loading rate and bioreactor size. In general, the higher the area loading rate, the more likely the bioreactor is to clog and back up. Once clogged, the bioreactor must be rested for at least four months to restore its treatment capacity.

To save space, some intermittent sand bioreactors are loaded up to 5 gal/ft^2/day. When loading bioreactors at this high of a rate, clogging can occur in as quickly as one to two years. Loadings of this rate are appropriate for seasonal use such as for a campground used only in the summer. Another option is to construct two or more bioreactor cells and carefully manage the whole system through alternating area loading onto the cells throughout the year. One management strategy is to divide the bioreactor into four cells as shown in Figure 11. During the warmest months of the year, rest one cell beginning in the spring (March through June) and one in the fall (July through October); do this while temporarily increasing the area loading rate to the other three. Continue to rest each of the other cells in the next year to complete a two-year management schedule. In this way, the per-cell area loading rate is lowest in the coldest time of the year, when biological activity is also at its lowest.

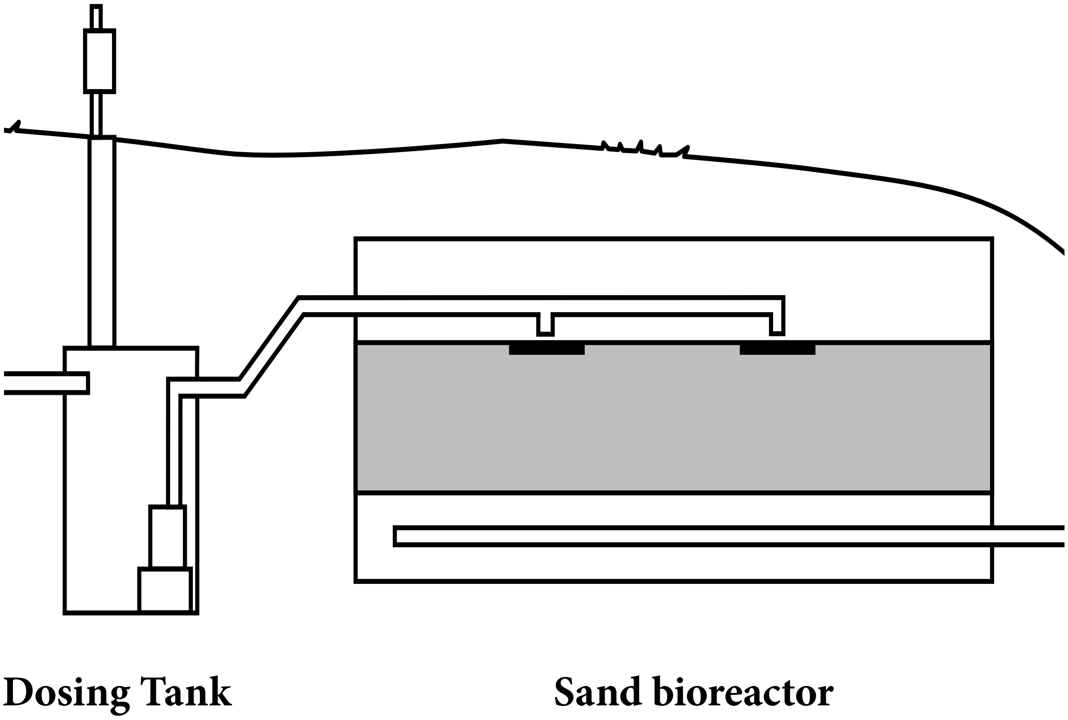
Rest Spring Year 1	Rest Spring Year 2
Rest Fall Year 1	Rest Fall Year 2

Figure 11. A management strategy for bioreactor systems with high loading rates.

Step 3: The loading rate for this intermittent sand bioreactor is determined to be 1 gal/ft^2/day.

Size: $\frac{360 \text{ gal/day}}{1 \text{ gal/ft}^2\text{/day}} = 360\ ft^2 = 10\ ft * 36\ ft$

Step 4. Select a wastewater application technique. For intermittent bioreactors, the frequency of dosing should be greater than 2 per day. Recirculating bioreactors require a different dosing strategy with more frequent doses. This is a result of the increased amount of water that must recirculate through the system. Examples of designs for recirculating bioreactors are in Appendix 2.



Step 4: For this system, use a 500-gallon dosing tank with a submersible effluent pump controlled by a float switch. When calculated using Bulletin 829, each dose will be about 50 gallons to fill the distribution system. Therefore, at full design load, the bioreactor could receive the following:

$$\frac{360 \text{ gal/day}}{50 \text{ gal/dose}} = 7.2 \textit{ doses per day}$$

Step 5. Determine wastewater pretreatment. Because treatment in a bioreactor is accomplished by natural flow through a media bed, particles in the wastewater are easily filtered out by the media and can quickly clog the bioreactor. Primary settling in a septic tank reduces the risk of surface clogging.

Septic tank effluent filters or screens around dosing pumps have also proven effective in protecting bioreactors from solids that escape the septic tank. Protecting sand bioreactors from excess solids is especially important for buried bioreactors, where periodic observations and management are difficult.

Fortunately, most solids carried over from septic tanks are biodegradable. If access to the media is possible, simply raking the surface to incorporate the solids into the bed of the bioreactor speeds up biodegradation. For buried bioreactors, resting for up to four months has proven effective in restoring a clogged bioreactor.

Greases from restaurants and other food-handling operations can quickly clog bioreactors. Removal of fats from wastewater through grease traps is currently recommended. Ongoing research on using sand bioreactors for high-grease-content wastewater is summarized in Box 2.

Box 2. Research is being conducted at The Ohio State University and elsewhere on how to use fixed media bioreactors to renovate wastewaters that contain grease. Here are some of the current findings:

- Animal fats and vegetable oils are degradable by microorganisms, but degradation is slow.
- Emulsifying agents play a key role in dispersing grease into smaller, more quickly degraded particles.
- Grease particles are easily trapped in beds of fixed media such as sand and textile, providing the contact time needed for microbial degradation.
- Hydraulic loading rates are important design and operational parameters for the treatment of food-processing wastewater. High dosing frequency is preferred for treatment.
- In sand bioreactors, gravel caps show potential as a pretreatment device. The gravel traps grease and initiates the degradation of fats and oils before final treatment in a sand bed. Textile caps over sand also show promise as a pretreatment device.
- Layered sand bioreactors of coarse over fine sand reduce the risk of clogging.

Step 5: For this system, use a 1,500-gallon septic tank with an effluent filter.

Step 6. Select a disinfection method. Fixed-media bioreactors by themselves do not filter out disease-causing organisms. Disinfection is needed before discharge or surface irrigation.

Ultraviolet (UV) light disinfection is an appropriate option for bioreactor effluent. When used properly, UV light will destroy bacteria, viruses, algae, and other microorganisms in renovated wastewater. UV light disinfection becomes more efficient as the amount of suspended solids in the effluent decreases. Therefore, sand bioreactors, with their extremely clear effluent, are especially well suited to UV light disinfection.

Chlorine is the most widely used disinfectant in the United States. It kills disease-causing organisms such as bacteria, viruses, and other microorganisms. A chlorine pellet called high-test hypochlorite (HTH) is the most commonly used chlorine formulation in on-site and small systems. Pellet-droppers are available and can be controlled with a timer to insure daily disinfection before discharge.

Ozone and other disinfection alternatives are available and should also be considered. For more information, access Ohio State University Extension Bulletin 943, *Disinfection to Protect Public Health*, available through local Extension offices in Ohio.

Step 6: For this system, install a chlorine pellet-dropper disinfection system at the irrigation tank.

Step 7. Select a discharge scenario. Effluent after disinfection can be discharged in one of three ways: drip irrigation, spray irrigation, or steam discharge with an NPDES permit. Because sand bioreactor effluent is extremely low in solids, low in ammonia, and low in $CBOD_5$, it is well suited for all three discharge scenarios.

Spray irrigation is described in detail in Ohio State University Extension Bulletin 860, *Reuse of Reclaimed Wastewater Through Irrigation*, and Bulletin 912, *On-site Sprinkler Irrigation of Treated Wastewater in Ohio*, available through local Extension offices in Ohio.

Drip irrigation of treated wastewater is also an option. The very low-solids content of bioreactor effluent and low BOD_5 make the effluent well suited for drip irrigation.

Stream discharge may be an acceptable option at some sites. Bioreactors produce very high-quality effluent; it can easily meet most NPDES permit requirements. UV light for disinfection is a good choice for a stream discharge system because most discharge permits restrict the use of chlorine.

Step 7: For this system, on-site spray irrigation will be used. (The system can be designed using Ohio State University Bulletin 912.)

How is a fixed-media bioreactor constructed?

A bioreactor can be constructed in one of two ways: by building it on-site (Figure 12a) or by premanufacturing it (Figure 12b). Building on-site is mainly used for heavy media such as sand, and for systems that treat large flows. Most manufacturers provide premanufactured systems of media other than sand with certain ranges of sizes.

When a system is built on-site, keeping groundwater and surface water out of the bioreactor is the single most important goal in construction. A liner, a cast-in-place tank, or a precast tank is required to keep groundwater out of the bioreactor. A liner or a tank is also used to keep untreated wastewater from entering groundwater. Covers, berms, and surface grading must be provided in such a way as to keep surface water from draining into a sand bioreactor.

Kits that include the liner, drain, and distribution system are available as shown in Figure 13.

Figure 12a. A bioreactor built on-site.

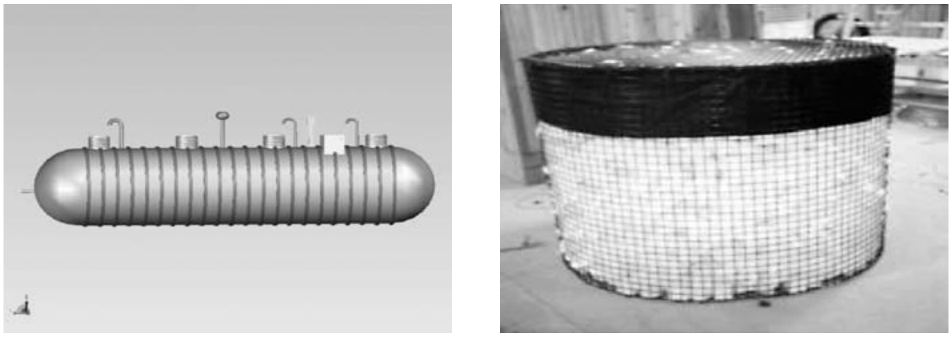


Figure 12b. Premanufactured bioreactor systems. (Source: www.winnsystems.com/envirofilter.html and www.waterloo-biofilter.com/products/wbs_mesh_basket_products.htm)

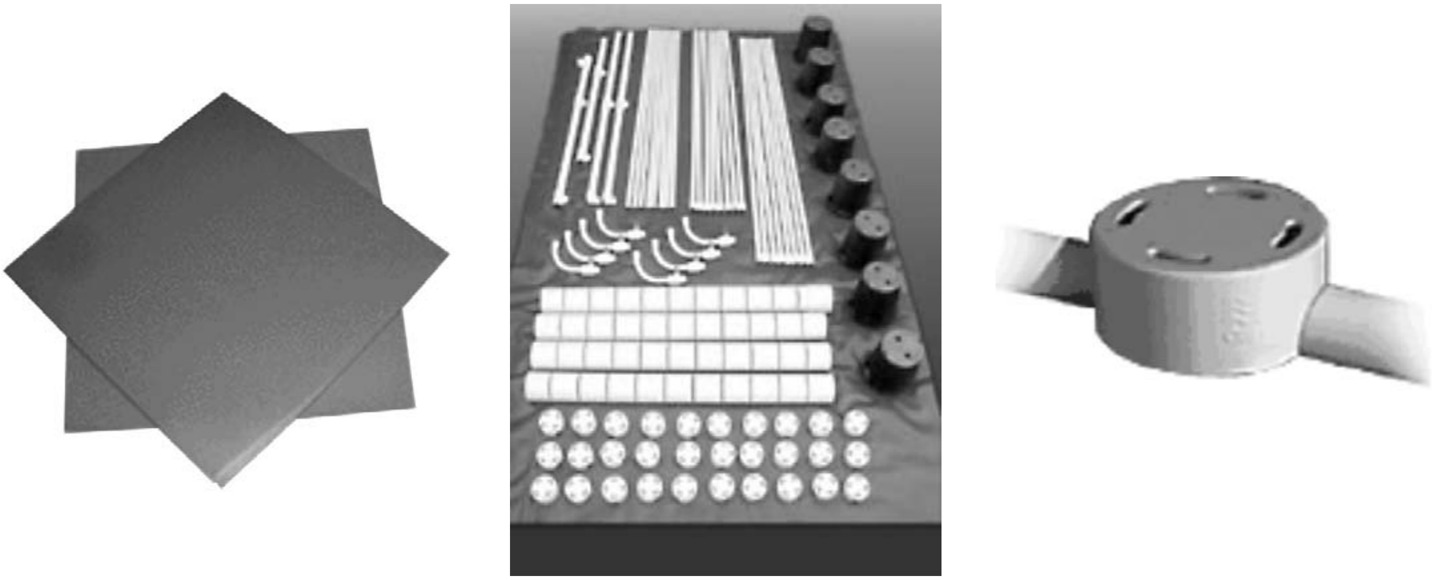


Figure 13. A liner and manifold kit for intermittent bioreactors. (Source: www.orenco.com)

A PVC liner of at least 20 mil is recommended in an earthen basin with provisions for UV protection. As with any liner system, it is important to use as few seams as possible. Because an outlet must penetrate the bottom of the liner, great care must be taken at this point to prevent leaks (Figure 14a).

A precast or a poured-in-place concrete tank is an alternative to a lined earthen basin. A tank once used for an aeration basin can be retrofitted with a drain, filled with suitable media, and a distribution system for use as a fixed-media bioreactor.

As with plastic-lined earthen basins, all connections through a concrete tank wall must be watertight. Boot seals are effective in eliminating infiltration at connections into concrete structures (Figure 14b).

Short circuiting through or around the media is another concern with bioreactors. Careful media placement to avoid internal layering is necessary to avoid forming internal clogging and channels. For on-site construction such as with sand bioreactors, dropping the media from a height of several feet should be avoided, because it promotes segregation by grain size. If sand layering is suspected, plow or rototill to redistribute the media.

Draining renovated wastewater from the bottom of a bioreactor is accomplished by simply sloping the bottom of the structure to an outlet. A layer of gravel should be placed at the bottom of the bioreactor to support the media and promote the free flow of effluent to the outlet.

Figure 14a. A boot for a liner. (Source: www.orenco.com)

Figure 14b. A boot seal for use in concrete tanks. (Source: www.polylok.com)

How is a fixed-media bioreactor operated and maintained?

Operation

It takes 4–8 weeks to start up a new bioreactor to produce a high-quality effluent. The effluent quality reflects the biofilm formation. Over the first few days of wastewater application, the effluent of sand systems may appear cloudy due to fine clay and silt particles that wash out of the sand. From then on, sand bioreactor effluent is extremely clear.

$CBOD_5$ levels and ammonia levels drop steadily after the first few days of wastewater application. When ambient temperatures are near 70°F, nitrification begins within the first two weeks of wastewater application, and full nitrification is observed within one month. The same pattern occurs at cooler ambient temperatures, but it will take longer to fully develop. To minimize start-up time and potential environmental impact, new bioreactors are best established during warm weather.

Once established, bioreactors are extremely resilient to fluctuations in loading. Short-term high loadings can stress the biofilm by decreasing the amount of air that flows through a more flooded bed of sand. However, research has shown that treatment performance remains high with overloading periods lasting less than two weeks.

The primary goal of sand bioreactor management is to manage clogging. Sand bioreactors are predisposed to clog over time. This is an important fail-safe feature that acts to protect the receiving environment from poorly treated wastewater. The predisposition to clogging also penalizes the negligent treatment system owner.

Routine Maintenance

1 **Check the bioreactor for surface ponding.** Wastewater should penetrate the media in a matter of minutes. If wastewater stands on the surface for even a few minutes, begin to take corrective action.

- It is possible that excess solids are being applied to the bioreactor surface. In this case, add some additional primary settling capacity, or add an outlet filter to improve the primary treatment performance (Figure 15). Rake the sand surface to break up and incorporate the solids that have collected on the surface. Also, if possible, rest the sand bed for up to four months.
- Check the media used to build the bioreactor. For sand, it may be finer than specified or have too high a uniformity coefficient. If this is the case, resting the sand for up to four months may restore the bioreactor. If the sand is indeed too fine or too non-uniform, continue to use the bioreactor, but at lower application rates. This most likely means the construction of an additional sand bed is required.
- Check the loading rate. Over time, water use may increase or water leaks may develop, causing the loading rate to be more than the design recommendations. Rest the bed for up to four months, and reduce the loading rate. This may mean finding and repairing water leaks or constructing an additional sand bed.
- Check the dosing system. Sometimes on/off switches malfunction and the necessary periodic dosing is compromised. A constant trickle application of wastewater will result in premature clogging. Rest the bioreactor for up to four months and restore the dosing system.

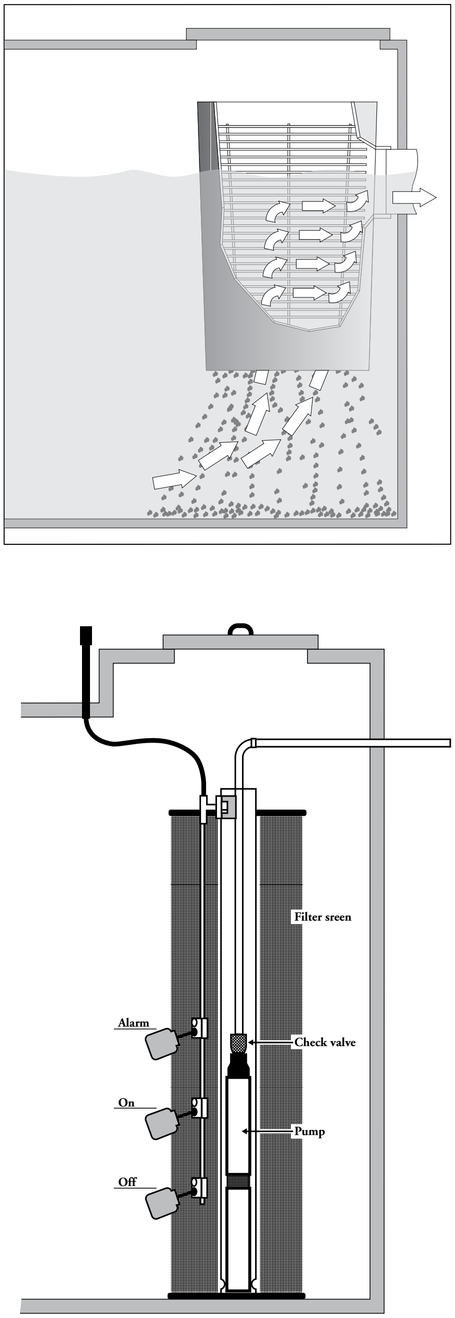


Figure 15. A septic tank effluent filter (top) and a pump chamber filter (bottom).

2 **Check ponding deep in the media bed.** Ponding deep in the media bed can be observed through an inspection port that extends down to the bottom of the media. Anaerobic conditions can develop deep in the media bed, causing the formation of a black mineral crust (iron sulfide) on the sand deep in the bioreactor. Bioreactor effluent will begin to show a brown stain when this occurs. When this begins, corrective action should be taken.

- Check the loading rate. Over time, water use may increase or water leaks may develop, causing the loading rate to be more than the design recommendations. Rest the bed for up to four months, and reduce the loading rate. This may mean finding and repairing water leaks or constructing an additional sand bed. Other techniques used to eliminate deep clogging are presented in Box 3.
- Check the BOD_5 of the wastewater being applied. Bioreactors described in this bulletin are intended for domestic sewage following primary treatment. Expected BOD_5 levels for this type of wastewater are between 75–150 mg/l. If the BOD_5 levels are a great deal higher than that, the surface loading rate must be reduced to prevent the creation of anaerobic conditions deep in the sand bed. Rest the media bed for up to four months. Most importantly, reduce the loading rate by constructing an additional bioreactor.

Box 3. What if resting is not possible?

An iron sulfide crust in a bioreactor can be oxidized quickly by treating it with hydrogen peroxide. Hydrogen peroxide is a strong oxidizing agent that decomposes to water. Operators who manage decades-old bioreactors in New York have used this technique to restore a clogged bioreactor.

To use this technique, deliver commercial-grade hydrogen peroxide to the bottom layers of a bioreactor through the bioreactor's discharge pipe. When treating only the clogged bottom layers of a bioreactor, the microbial film that formed in the top layers is unaffected. The treated bioreactor can then be put back into service quickly and can once again provide full treatment of wastewater. Care and protective clothing are required for hydrogen peroxide treatment. When the peroxide makes contact with organic matter, foaming occurs and the mixture expands.

For small systems, treating the septic tank as a holding tank is a resting option. With severe water conservation measures in place, sewage can be pumped from the septic tank every 1 to 2 weeks and hauled to a treatment plant while the bioreactor is resting.

3 **Check the dosing system.** Because they are mechanical systems, pumps with electrical connections should be checked at least once a year.

- Conduct a simple pump test to check the performance of the pump, the switches, and the alarm system. If possible, begin by turning off the power to the pump and filling the dosing tank with water up to the emergency level. Turn on the power. The emergency light or alarm should be activated, and the pump should come on.
- To check the dose volume, fill the tank with water until the pump turns on. Then, measure the water level in the tank. Continue to pump out water until the pump turns off. Then, measure the water level again. Compare the drop in inches to the original settings, and based on the inside dimensions of the tank, calculate the dose volume. Use the calculations in the highlighted box below for round and rectangular tanks.
- Check the dosing tank for apparent leaks that are bringing excess water into the tank. Look for leaks around the tank inlet and outlet pipes and around the access port.
- Visually inspect the wiring for signs of wear, cracks, corrosion, or rodent damage. Do not touch the wiring, because electrical shock is a risk. Remember that the inside of a pumping chamber is a wet, corrosive environment, so don't make any electrical connections inside the tank. If damage is evident, rewiring is probably necessary. For more information on proper wiring, access the Ohio State University Extension Bulletin 829, *Mound System: Pressure Distribution of Wastewater Design and Construction in Ohio*, available through local Extension offices in Ohio.

Round Tank:

$$\text{Gallons per inch of depth} = \frac{\text{tank diameter in inches} * \text{tank diameter in inches}}{294}$$

Rectangular Tank:

$$\text{Gallons per inch of depth} = \frac{\text{tank width in inches} * \text{tank length in inches}}{231}$$

Table 2. Estimated pumping frequency (in years)*.

Tank Size (gal)	*Number of household members*									
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
500	5.8	2.6	1.5	1.0	0.7	0.4	0.3	0.2	0.1	-
750	9.1	4.2	2.6	1.8	1.3	1.0	0.7	0.6	0.4	0.3
1000	12.4	5.9	3.7	2.6	2.0	1.5	1.2	1.0	0.8	0.7
1250	15.6	7.5	4.8	3.4	2.6	2.0	1.7	1.4	1.2	1.0
1500	18.9	9.1	5.9	4.2	3.3	2.6	2.1	1.8	1.5	1.3
1750	22.1	10.7	6.9	5.0	3.9	3.1	2.6	2.	1.9	1.6
2000	25.4	12.4	8.0	5.9	4.5	3.7	3.1	2.6	2.2	2.0
2250	28.6	14.0	9.1	6.7	5.2	4.2	3.5	3.0	2.6	2.3
2500	31.9	15.6	10.2	7.5	5.9	4.8	4.0	3.4	3.0	2.6

*Note: More frequent pumping is needed if a garbage disposal is used.

4 **Check the septic tank for necessary pumping.** See Table 2.

5 **Check the condition of the septic tank inlet and outlet baffles.** If a baffle is damaged or missing, replace it with a sanitary tee. Also, consider replacing the outlet baffle with an outlet filter to reduce the amount of solids discharged to the bioreactor (Figure 15).

6 **Measure the wastewater flow to check for leaks and excessive water use.** In time, excess wastewater can cause the pump to fail prematurely or the bioreactor to clog. A simple event counter records how frequently a pump comes on. Household water meters can be checked for evidence of excess water use.

7 **Maintain the bioreactor surface, roof, or earthen cover.** Tree roots can clog pipes in a buried bioreactor, so keep trees from growing on the earthen cover. For a covered bioreactor, check the roof for leaks.

8 **Watch for changes in surface water drainage.** Excess water is the greatest threat to the proper performance of a bioreactor. Changes in landscaping near the bioreactor may divert excess drainage water and overwhelm the bioreactor, causing premature clogging. Watch out for surface drainage when new roads or driveways are constructed in the area. Also, divert drainage from nearby building roofs.

Diagnosing Problems

Even with fluctuating waste loading, fixed-media bioreactors have a reputation of producing extremely high-quality effluent. Sometimes an individual reactor is plagued with poor performance. Poor performance is usually the result of short circuiting through the bioreactor. Short circuiting can occur along the edges of the bioreactor if the bioreactor is neglected and allowed to pond. Short circuiting may also occur along discharge, vent, or inspection pipes that extend through the sand. Diversion collars placed around the pipes, just below the bioreactor surface, can be retrofitted if this begins to happen. Channels through the media are another source of short circuiting. Channels seldom form if wastewater is applied in small doses. Though rare, channels are difficult to predict. Even when all the other bioreactors in a system have been built at the same time, in the same way, and with the same materials, channeling can take place in one and not any of the others. Try to eliminate channeling by using the following four-step process:

1. Check the switches and timers in the application systems to make sure the bioreactor is receiving only small doses of wastewater spaced throughout the day.
2. Till the surface of the bioreactor with a rototiller or moldboard plow.
3. Remove all of the sand from the bioreactor and put it back in again.
4. As a last resort, replace the sand with new sand.

Appendix I: Sand Size Analysis for On-Site Wastewater Treatment Systems

Size distribution is one of the most important characteristics of sand treatment media. Sand bioreactor clogging is usually the result of using sand that is too fine, has too many fines, or has a weak or platy structure. The most important feature of the sand is not the grains, but rather the pores the sand creates. The treatment of wastewater occurs in the pores, where suspended solids are trapped, microorganisms grow, and air and water flow. Determination of size distribution of sand particles is a direct measurement of sand media structure. It is usually measured as the effective size and the uniformity coefficient. For example, ideal sands for intermittent bioreactors are a medium to coarse sand with an effective size (D10) between 0.3 mm and 1.0 mm. The uniformity coefficient should be less than 4.0 (D60/D10). Less than 4% of the sand should be fine (pass through a #200 sieve).

To determine the effective size and uniformity coefficient, the sand is dried and then sieved through a series of screens. Then, the weight of the sand on each sieve is measured. The sand grain diameter at which 10% of the sand is finer and 90% is bigger is the D10. D10 is the sand effective size. To determine the uniformity coefficient, the D60 is also determined. The sand diameter at which 60% is finer and 40% is bigger is the D60. The uniformity coefficient is D60/D10 and an indicator of the range of grain sizes. If the number is large, the sample contains grains with many different sizes. If the uniformity coefficient is 1, all grains are the same size.

The Ohio EPA requires that owners and operators of sand bioreactors use certified sand—sand that is tested through a sieve analysis and that meets the criteria of one of the following standards: (a) ASTM C136, “Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates” or (b) ASTM D451, “Standard Method for Sieve Analysis of Granular Mineral Surfacing For Asphalt Roofing Products.”

How is a sieve analysis conducted?

In a sieve analysis, sand is shaken and sorted through a set of sieves of progressively smaller sizes. The following list reflects the apparatus needed for a sieve analysis:

- Scale (or balance) with a +0.1g accuracy
- No. 200 sieve
- Set of sieves, a lid, and a receiver. Select suitable sieve sizes (Table 3) to obtain the required information as specified, for example Nos. 3/8”, 4, 10, 20, 40, and 60.
- Drying oven with temperature at 110+/-5°C (230+/-9°F)
- Metal pans, one for each sieve size plus one for a sample
- Mechanical sieve shaker (optional)

Table 3. Sieve number (ASTM–E11) and mesh size.

No.	Mesh Size (mm)	No.	Mesh Size (mm)	No.	Mesh Size (mm)	No.	Mesh Size (mm)
1”	25.0	7	2.80	20	0.85	60	0.250
3/4”	19.0	8	2.36	25	0.71	80	0.180
1/2”	12.5	10	2.00	30	0.60	100	0.150
3/8”	9.5	12	1.70	35	0.50	120	0.125
4	4.75	14	1.40	40	0.425	140	0.106
5	4.00	16	1.18	45	0.355	170	0.090
6	3.35	18	1.00	50	0.300	200	0.075

During the analysis, the sand will be collected and weighed in metal pans, so a set of pans must be cleaned, labeled, and pre-weighed. The sand is first dried in an oven and then weighed. Then, it is washed to capture any fine dust. The dust is the material that will wash through a No. 200 sieve. After the washed sand is dried again, the sand is shaken through a set of sieves to determine the distribution of sizes. The step-by-step procedure is listed here.

1. Label a set of metal pans with sieve size and weight. Then, record each sample pan (PAN WEIGHT) and set it aside.
2. Begin with about a 100-gram sample of sand. Put the sand in a metal pan and dry it in a 105°C–115°C oven for two hours. Weigh the dry sand sample with the pan (DRY PAN WEIGHT). Then, subtract the weight of the pan: TOTAL SAMPLE WEIGHT = DRY PAN WEIGHT – PAN WEIGHT.
3. Fill the pan and sand sample with tap water, shake the pan, and decant wash water through a No. 200 sieve. Wash the material retained on the sieve back into the pan. Repeat several times until the wash water is clear. Dry the sample again in a 105°C–115°C oven for two hours. Weigh the dry, washed sand sample with the pan (WASHED PAN WEIGHT). Then, subtract the weight of pan: WASHED SAND WEIGHT = WASHED PAN WEIGHT – PAN WEIGHT. Subtract WASHED SAND WEIGHT from TOTAL SAMPLE WEIGHT to determine % fines: % FINES = ((TOTAL SAMPLE WEIGHT – WASHED SAND WEIGHT) / TOTAL SAMPLE WEIGHT) * 100
4. Arrange a set of sieves from largest opening to smallest, with the pan below the bottom sieve (Figure 16). Place the sample on the top sieve, and place the lid over the top sieve.
5. Shake the stacked sieves, vibrating, jogging, and jolting them by hand or by mechanical apparatus. Keep the sand in continuous motion for a sufficient period such that not more than 1% by weight of the residue on any individual sieve will pass that sieve during 1 minute of additional hand sieving. Five to ten minutes of original sieving will usually accomplish this criterion.
6. Pour the sand off each sieve into labeled, weighed pans. Weigh and determine the SAMPLE WEIGHT by subtracting the weight of the pan.

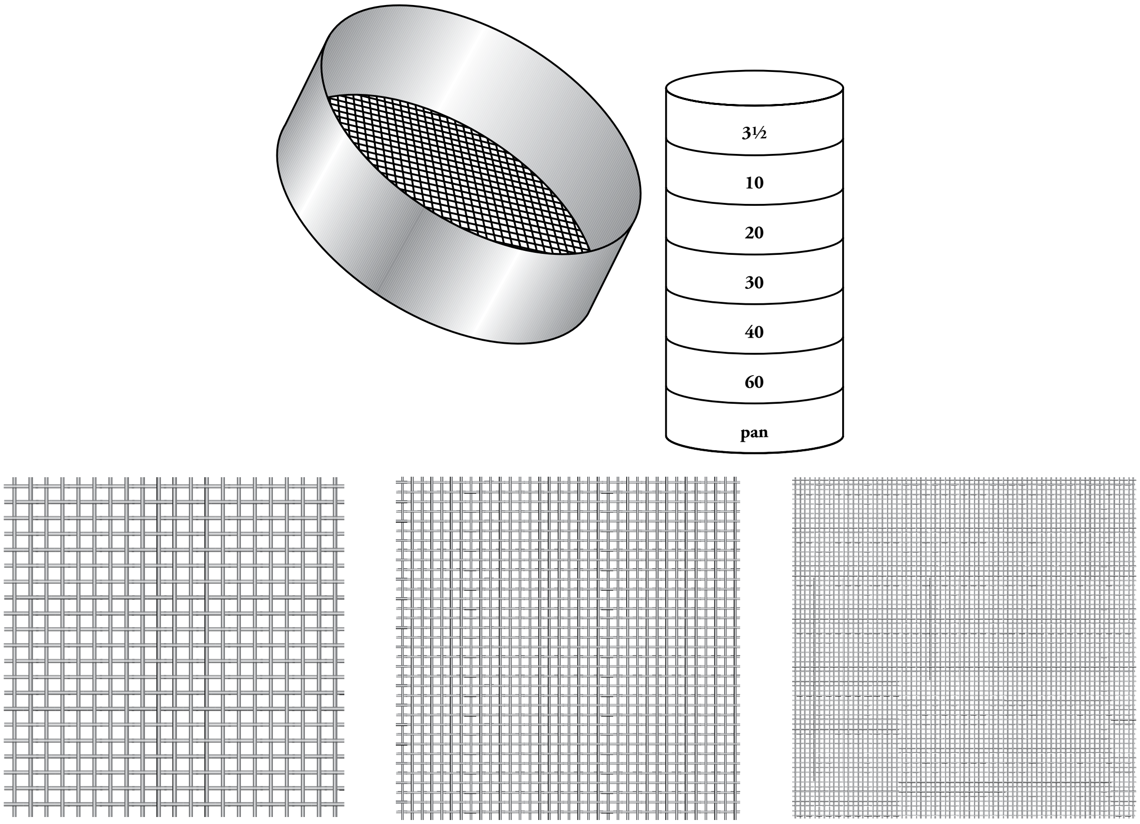


Figure 16. Sieves with various-sized openings are used for sand analysis. The sieves are arranged largest to smallest from top to bottom.

How is a sieve analysis recorded and calculated?

Record all the weights on the blank Report Form below and determine the percent passing for each sieve. (Refer to the example Report Form on page 24.)

$$\text{Percent of material retained on the sieve} = \frac{\text{SAMPLE WEIGHT}}{\text{TOTAL SAMPLE WEIGHT}} \times 100\%$$

Percent passing = percent passing the next largest sieve – percent retained on sieve

Graph the percent passing results on the Figure 18 semi-log paper as shown in the Figure 17 example. From the graph, find the D10, where only 10% of the sample is a smaller size. Also from the graph, find the D60, where 60% of the sample is a smaller size. The uniformity coefficient is D60/D10.

Report Form (Blank)

Project: ______________________________ Date: ____________________ Test by: __________________

Sample Material: __________________ Sample I.D.: ______________________

PAN WEIGHT (g): __________________ DRY PAN WEIGHT (g): ______________ WASHED PAN WEIGHT (g): __________

WASHED SAND WEIGHT (g): __________ TOTAL SAMPLE WEIGHT(g): __________ FINES WEIGHT, WF (g): ___________

Sieve number	Sieve size (mm)	PAN WEIGHT	SAMPLE PAN WEIGHT	SAMPLE WEIGHT	% retained	% passing next larger sieve	% passing

Effective Size = D10 =
Uniformity Coefficient = D60/D10 =
% Fines = ((Total Sample Weight – Washed Sand Weight) / Total Sample Weight) ∗ 100 =

Report Form (Example)

Sieve number	Sieve size	SAMPLE WEIGHT (g)	% retained	% passing next larger sieve	% passing
3.5	5.60	6.00	5	100	95
10	2.00	8.40	7	95	88
20	0.85	57.60	48	88	40
30	0.60	14.40	12	40	28
40	0.425	12.00	10	28	18
60	0.25	15.60	13	18	5
pan	--	6.00	5	5	--
TOTAL SAMPLE WEIGHT	--	120.00			

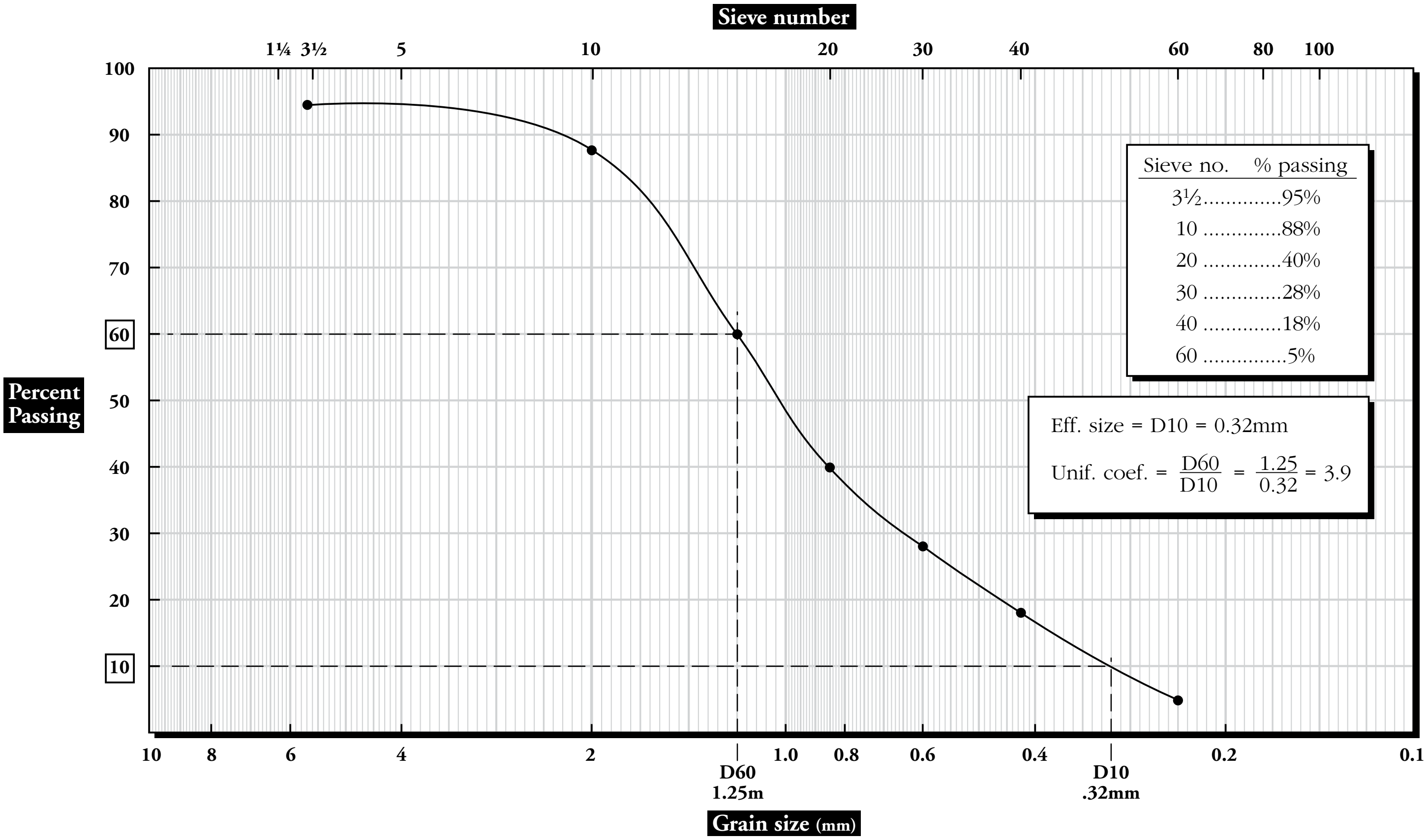


Figure 17. Graph of sand sieve analysis (example) to determine effective size and uniformity coefficient.

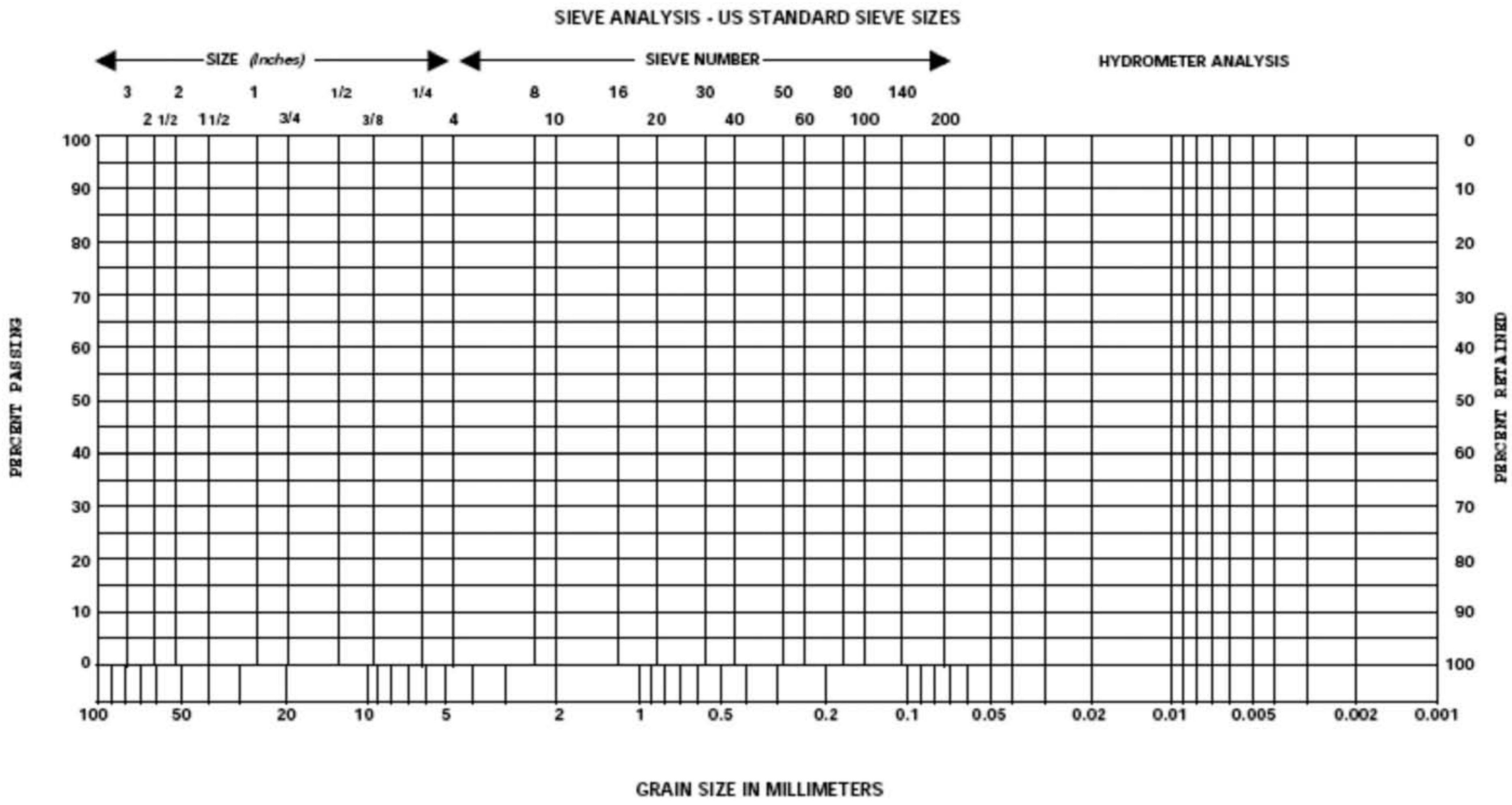


Figure 18. Graph of sand sieve analysis (blank) to determine effective size and uniformity coefficient.

Appendix II: More Design Examples

Design Example II: Recirculating Textile Bioreactor

A community library needs a wastewater treatment system to replace an old, failed soil absorption system. Much of the land owned by the library has been paved for parking. The paving even covered up the old septic system, which likely contributed to its failure. Only a 15x25 foot area is available for a wastewater treatment system, and a nearby stream could be considered for a discharge. The library has the equivalent of 6 full-time employees (6 FTE).

*Design wastewater flow: 6 FTE * 45 gal/employee/day = 270 gal/day*

Step 1. Propose: A recirculating textile bioreactor to fit in this small space.

The manufacturers of the filter media will provide the design information, including the area loading rate, bioreactor size, wastewater application method, and recommendations for disinfection and discharge. For a project with a small flow of 270 gal/day, they will supply a premanufactured system and install it on-site (Figure 19).

Step 2. Bioreactor depth: 2 feet.

Step 3. Area loading rate and bioreactor size:

Forward flow loading rate: 5 gal/ft^2/day

Recirculation ratio: 4:1

Actual loading rate = Forward flow loading rate * recirculation factor = 5 gal/ft^2/day * (4 parts recirculated effluent + 1 part sewage) = 5 * 5 = 25 gal/ft^2/day

Size: $\frac{270\text{ gal/day}}{5\text{ gal/ft}^2\text{/day}} = 54\text{ ft}^2$ (therefore a 6 ft * 10 ft bioreactor is sufficient)

Step 4. Wastewater application:

Technique: The wastewater in the recirculation basin is directed to a submersible effluent pump and is distributed across the filter bed using a series of fixed spray nozzles.

Total application per day = 25 gal/ft^2/day * 60 ft^2 = 1,500 gal/day

Dosing frequency: 24 times/day

Dose volume: $\frac{1{,}500\text{ gal/day}}{24\text{ doses/day}} = 63\text{ gal/dose}$

Step 5. Pretreatment: Septic tank with an effluent filter.

Step 6. Disinfection: UV disinfection unit.

Step 7. Discharge: Stream discharge with an NPDES permit.

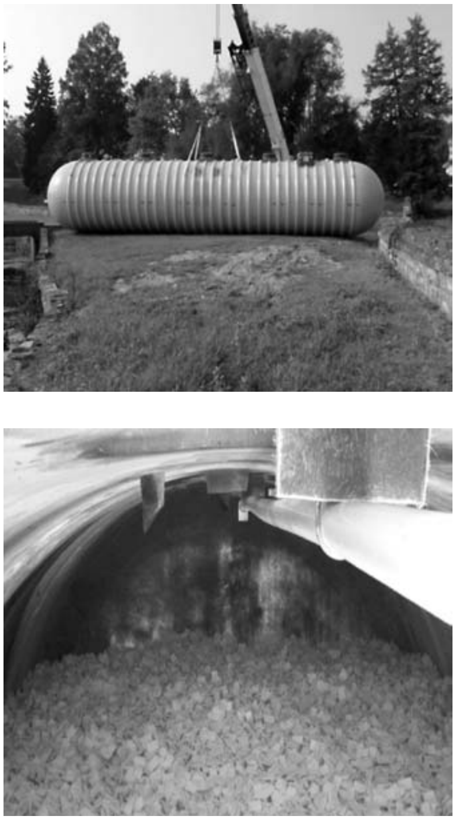


Figure 19. Examples of installations of premanufactured textile bioreactors. (Source: www.winnsystems.com)

Design Example III: Recirculating Sand Bioreactor

A developer is planning an executive housing development for 25 homes. An elaborate, landscaped entrance and roadway is planned, and wastewater is being considered for irrigation. Appearance, odors, noise, and space are all limitations.

*Design wastewater flow: 25 homes * 5 bedrooms * 120/gal/bdrm/day = 15,000 gal/day*

Step 1. Propose: A sand bioreactor system for this community with the aesthetic considerations in mind.

Sand characteristics: ES = 1.2 mm, UC $\leq$ 4

Step 2. Bioreactor depth: 2 feet.

Step 3. Area loading rate and bioreactor size:

Forward flow loading rate: 5 gal/ft^2/day

Recirculation ratio: 4:1

Actual loading rate = Forward flow loading rate * recirculation factor = 5 gal/ft^2/day * (4 parts recirc. effluent + 1 part sewage) = 5 * 5 = 25 gal/ft^2/day

Size: $\frac{15{,}000 \text{ gal/day}}{5 \text{ gal/ft}^2\text{/day}} = 3{,}000 \text{ ft}^2$ (or 6 reactors, each 10 ft * 50 ft)

Step 4. Wastewater application:

Technique: The wastewater in the recirculation tank is directed to a submersible effluent pump and is distributed across the filter bed through a small-diameter perforated pipe.

Total application per day = 25 gal/ft^2/day * 3,000 ft^2 = 75,000 gal/day

Dosing frequency: 72 times/day

Dose volume: $\frac{75{,}000 \text{ gal/day}}{72 \text{ doses/day}} = 1{,}042 \text{ gal/dose}$

Dose volume per bioreactor = $\frac{1{,}042 \text{ gal/dose}}{6 \text{ bioreactors}} = 174$ gal/dose/bioreactor

Step 5. Pretreatment: Septic tank with an effluent filter.

Step 6. Disinfection: Not needed for subsurface dispersal.

Step 7. Discharge: Drip irrigation system.

Sand criteria for non-limestone sand for use in recirculating bioreactors.

Discharge requirement	Effective Size(mm)	UniformityCoefficient
Low effluent BOD$_5$	0.5 - 1.5	less than 4

References

Crites, R. and G. Tchobanoglous. *Small and Decentralized Wastewater Management Systems*. Boston: McGraw-Hill, 1998.

DeS Furman, T., W.T. Calaway, and G.R. Grantham. "Intermittent Sand Filters: Multiple Loadings." *Sewage and Industrial Wastes*. 27.3 (1955): 261–274.

Kang, Y.W., K. Mancl, and O. Tuovinen. "Treatment of Turkey Processing Wastewater with Sand Filtration." *Bioresource Technology*. 98.7 (2007): 1460–1466.

Kang, Y.W., K. Mancl, and O. Tuovinen. "Recovery of Sand Bioreactor Performance Through Resting Following Treatment of Turkey Processing Wastewater." *Applied Engineering in Agriculture*. 23.6 (2007a): 719–725.

Mancl, K. and J. Peeples. "One Hundred Years Later: Reviewing the Work of the Massachusetts State Board of Health on the Intermittent Sand Filtration of Wastewater from Small Communities." Proceedings of The Sixth National Symposium on Individual and Small Community Sewage Systems. ASAE. 1991.

Tao, J., K. Mancl, and O. Tuovinen. "A Potential Sanitary Sewer Overflow Treatment Technology: Fixed Media Bioreactors." Water Environment Research. 2011.

US EPA. Office of Water Program Operations. *Onsite Wastewater Treatment and Disposal Systems*. EPA 625/1-80-012. Washington DC: EPA, 1980.

Widrig, D., J. Peeples, and K. Mancl. "Intermittent Sand Filtration for Domestic Waste Water Treatment: Effects of Filter Depth and Hydraulic Parameters." *Applied Engineering in Agriculture*. 12.4 (1996): 451–459.

Xi, J., K.M. Mancl, and O.H. Tuovinen. "Carbon Transformation During Sand Filtration of Cheese Processing Wastewater." *Applied Engineering in Agriculture*. 2.2 (2005): 271–274.

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