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Design of Fluidized-Bed, Biological Denitrification Systems

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CHEMICAL TECHNOLOGY DIVISION

NUCLEAR WASTE PROGRAMS

Biological Denitrification

(Activity No. AP 05 25 15 0; FTP/A No. ONLWL11)

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DENITRIFICATION SYSTEMS

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DESIGN OF FLUIDIZED-BED, BIOLOGICAL DENITRIFICATION SYSTEMS

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ABSTRACT

Many commercial processes yield nitrate-containing wastewaters that are being discharged to the environment because traditional recovery or disposal methods are economically unacceptable. The anticipated discharge limits [i.e., 10 to 20 g (NO₃⁻)/m³] being considered by many states will not allow continued release of these wastewaters. The new discharge standards can be met economically by use of the fluidized-bed, biological denitrification process.

Research and development studies were conducted with 0.05-, 0.10-, 0.20-, and 0.50-m-diam fluidized-bed bioreactor systems. Feed nitrate concentrations were in the 0 to 10,000 g (NO₃⁻)/m³ range. Using the data from these studies, rate expressions were developed for the destruction of nitrate as a function of nitrate concentration. Methods were also developed for sizing bioreactors and biomass control systems.

The sizing methods for fluidized-bed denitrification systems are described, and support systems such as sampling and analysis, instrumentation and controls, utilities, and bacteria storage are discussed. Operation of the process is also briefly discussed to aid the designer. Using the methods presented in this report, fluidized-bed, biological denitrification systems can be designed to treat nitrate wastewater streams.

1. INTRODUCTION

Many commercial processes such as fertilizer production, paper manufacturing, and metal finishing, as well as several steps in the nuclear fuel cycle, yield nitrate-containing wastewaters that are currently being discharged to the environment because traditional recovery or disposal methods are economically unacceptable. Nitrate-containing wastewater causes stream eutrophication and can be a health hazard. In

addition, the anticipated discharge limit [i.e., 10 to 20 g (NO₃⁻)/m³] being considered by many states will not allow the continued release of these wastewaters.

These discharge standards can be met economically by application of the fluidized-bed, biological denitrification process. This report presents data from an extensive research and development (R&D) program that can be used in the design of full-scale fluidized-bed, biological denitrification facilities.

It has been estimated that as many as 2.5 million tons of dissolved-nitrogen-bearing substances reach the surface waters of the United States each year.¹ The nitrogen waste discharged directly from industrial installations is estimated to be 20% of the total.² Much of this nitrogen pollution is in the form of dissolved nitrates at high concentrations, which can contribute to eutrophication and can also constitute a health hazard.^{3,4} Consequently, rigorous standards are being established for nitrates released in industrial effluents.

Standards for industrial liquid-waste discharges are controlled by the U.S. Environmental Protection Agency (EPA), state water-quality boards, and, occasionally, local regulations. These groups have established standards for some regions of the United States, but no nationwide standards for limiting the nitrate content in wastewater have been enacted. There are indirect limits on excessive nitrate discharges, such as one regulation which states: "Other pollutants shall not be added to the water in quantities that may be detrimental to public health or impair the usefulness of the water as a source of domestic water supply."⁵ The EPA has established 10 g of nitrate (as N) per cubic meter to be the upper limit for potable water.⁶ The Y-12 Plant* is currently restricted to 45 g/m³ atomic nitrogen in an effluent, with indications that restrictions will become even more stringent in the future, probably approaching 10 g NO₃⁻(N)/m³. Some limits will probably be uniformly imposed by 1983, but the exact limits are not now known; levels of 10 to 15 g NO₃⁻(N)/m³ have been proposed by some state regulation boards.

* Operated by Union Carbide Corporation in Oak Ridge, Tennessee, for the Department of Energy.

Disposition of the nitrate (recovery, conversion, or discharge) will be governed by the economics of the process technologies that may be applied. In situations where nitrate recovery is not feasible, the reduction of nitrous oxides to nitrogen gas (chemically or biologically) appears to be the only acceptable long-range solution.

Although attempts have been made to evade the liquid waste-nitrate problem by volatilization into a gaseous effluent, this practice will probably not meet future EPA restrictions. In cases where nitrate cannot be economically recovered, biological denitrification is the apparent preferred process because the end-product nitrogen gas, carbon dioxide, and biomass are ecologically acceptable; in addition, it is more economical than chemical reduction.⁷

The biodenitrification process, as developed at ORNL, biologically reduces nitrate or nitrite to gaseous molecular nitrogen in a fluidized-bed reactor operated in liquid plug flow. This process has been developed through the pilot-plant stage and is ready for industrial application.

2. BIOLOGICAL DENITRIFICATION PROCESS

2.1 Feed Requirements

The feed should contain those components which enhance biological denitrification while minimizing the components which inhibit the denitrification process. The feed stream must supply the essentials for bacterial life. These essentials are a carbon source, micro-nutrients, and nitrate for biological reduction. Although nitrate is required, it is accompanied by a complementary cation which can inhibit denitrification at high levels. Inhibition may also occur when low levels of metals such as nickel are present in the feed stream.

2.1.1 Nitrate feed requirements

The denitrification rate increases with increasing nitrate concentration; therefore, it is advantageous to use the maximum nitrate concentration in the feed stream without inhibiting the denitrification rate. The inhibition that occurs at high nitrate concentration is believed to

be caused by the high concentration of the complementary cation. Earlier work has shown that denitrification is highly dependent on available phosphorus. Some complementary cations may complex the phosphorus, thereby decreasing the rate of denitrification caused by a phosphorus deficiency.⁸ Table 1 gives some upper limits of cation feed concentrations that were determined in development work.⁹

Table 1. Concentration limits of complementary cations

| Cation | Concentration (g/L) |
|------------------|------------------------|
| NH_4^+ | 0-20 |
| Na^+ | 0-40 |
| Ca^{2+} | 0-50 |

Pilot-plant tests at a nitrate concentration of 10 g/L with either Ca^{2+} or Na^+ as cations resulted in high denitrification rates with no signs of inhibition. Higher concentrations of nitrate have not been used in extensive tests.

2.1.2 Additives required

A carbon source is required for denitrification. Several carbon sources that have been used successfully include ethanol, methanol, acetate, and citrate. These carbon sources may be used either separately or mixed. Ethanol was used in the majority of development work because it could be easily determined in the presence of other soluble carbon compounds by using the ethanol Calbiochem kit.¹⁰ The carbon source should be added to maintain the ratios of carbon to nitrogen (C:N) in the feed between 1.1 and 1.4.

Several micronutrients are required to enhance the denitrification process. Sodium phosphate is metered into the feed stream as it enters the bioreactor. The concentration of sodium phosphate in the feed is adjusted to maintain a 5-g/m³ residual of phosphate in the effluent. In pilot-plant studies, the sodium phosphate concentration of the feed was 40 g/m³. Other micronutrients needed for successful growth are listed in Table 2;⁷ the concentration of antifoam given may be increased if excess foaming occurs.

Table 2. Feed additives

| | |
|---|-------|
| Additive mix, mg/g NO ₃ ⁻ | |
| MgSO ₄ | 3.4 |
| Dow-Antifoam "A" | 3.4 |
| Trace metal solution | 0.34 |
| Trace metal solution mix, g/L | |
| H ₃ BO ₃ | 1.0 |
| ZnSO ₄ · 7H ₂ O | 0.4 |
| (NH ₄) ₆ Mo ₇ O ₂₄ · 4H ₂ O | 0.2 |
| MnSO ₄ · 7H ₂ O | 0.25 |
| CuSO ₄ · 5H ₂ O | 0.45 |
| FeSO ₄ · 7H ₂ O | 0.25 |
| KI | 10.0 |
| Fe-chelate | 200.0 |

2.1.3 Impurities

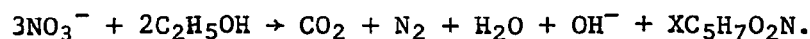
Some impurities such as heavy metals inhibit denitrification. Since the pH of the feed stream must be maintained in the 7.0 to 9.5 range for denitrification, the solubility of these toxic metals is low. If pH adjustment is required in feed preparation, care should be taken to remove precipitated metals before feeding the column. The short contact times in fluidized-bed bioreactors guards against the poisoning of the bacteria by pulses of toxic material, because the material passes through the system before it can cause a large decrease in the bacteria population.

2.2 Fluidized-Bed, Biological Denitrification Process

The naturally occurring biological denitrification reaction has been applied in fluidized-bed reactors. The process has the advantages of plug-flow operation. By using different modes of operation, the process can be adapted to numerous wastewater treatment applications.

2.2.1 Microbiology of biological denitrification

Biological denitrification is the biological reduction of nitrate or nitrite to gaseous molecular nitrogen. It commonly occurs in soil under anaerobic conditions by the various strains of facultative anaerobic bacteria which are responsible for recycling nitrogen compounds to the atmospheric, molecular nitrogen pool. The reaction requires a carbon source, which has been successfully supplied in the form of various alcohols and acetates. With ethanol as the carbon source, the reaction may be written in unbalanced form as:



The coefficients on nitrate and ethanol in the chemical equation reflect the observation that the molar ratio of carbon consumed to nitrogen (as nitrate) reacted is about 1.1 to 1.4. The approximate composition of the biomass is $\text{C}_5\text{H}_7\text{O}_2\text{N}$. The biomass yield is ~0.1 g per gram of nitrate consumed.¹¹ The mixed bacterial population is isolated from garden soil and contains predominantly *Pseudomonas*. A schematic representation of the chemical flow paths in the denitrifying microorganism is shown in Fig. 1. As these bacteria grow, they readily attach themselves to almost any solid surface available; thus adherence to the particles in a fluidized bed is a naturally occurring mechanism.

2.2.2 Process description

The naturally adhering property of these denitrifying bacteria can be utilized to achieve high rates of denitrification in fluidized-bed bioreactors. Biomass adhering to particles (30- to 60-mesh anthracite coal is recommended) is fluidized by the upward flow of the nitrate wastewater through the bioreactor. Bubbles of molecular nitrogen formed during denitrification rise in the bioreactor and are vented to the atmosphere. Biomass growth in the bioreactor is controlled by removing biomass-laden particles and forcing them through a 30-mesh vibrating screen to remove excess biomass. The "clean" particles are returned to the same bioreactor in the feed stream. Using this method of control, the bacteria loading in the bioreactor can be maintained in the desired 10 to 20% on a dry-weight basis. A basic process flowsheet is shown in Fig. 2.

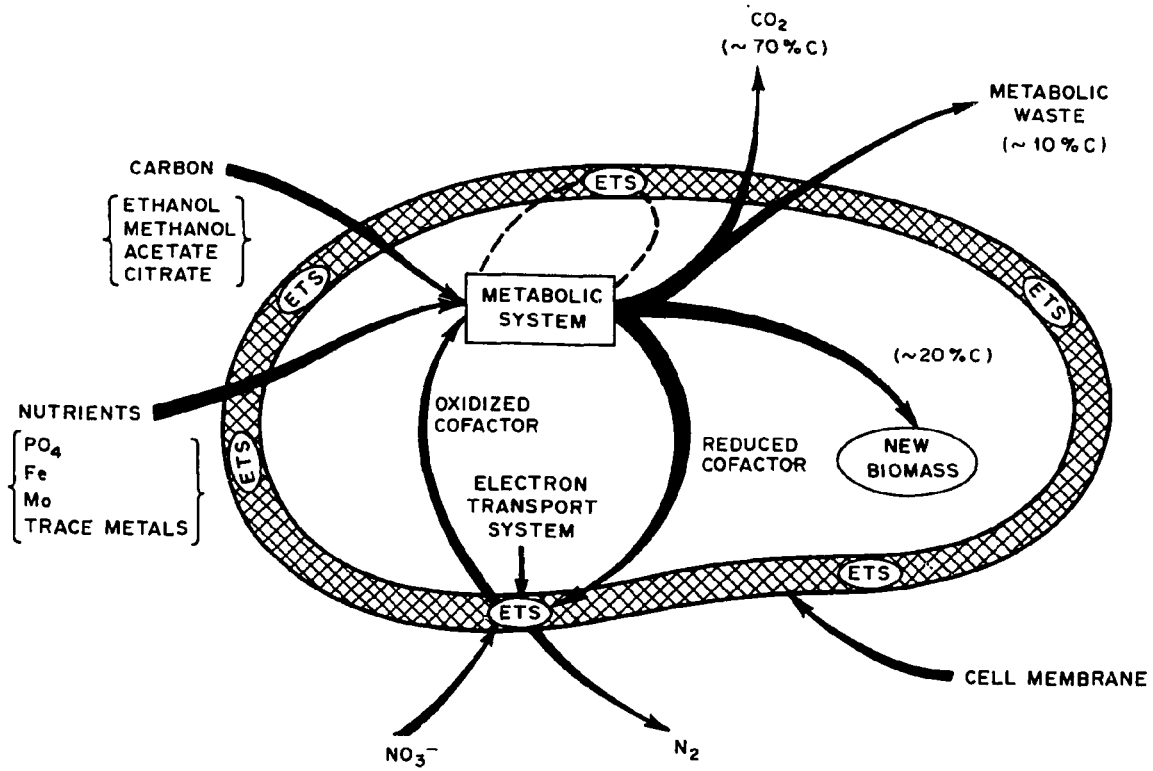


Fig. 1. Schematic of chemical flow paths in denitrifying bacteria.

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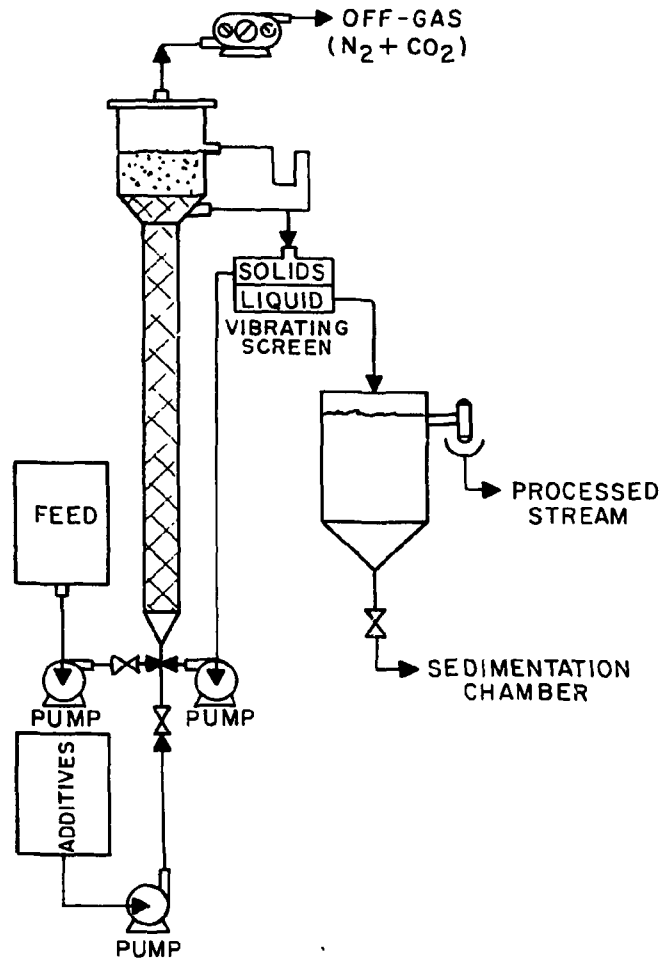


Fig. 2. Basic process flowsheet for biological denitrification.

2.2.3 Process modes of operation

The basic process flowsheet module given in Fig. 2 can be used to develop several modes of operation, and the single bioreactor is the simplest mode. Multiple bioreactors can be operated in series or in parallel. A typical flowsheet for two bioreactors in series is given in Fig. 3.

If the cost or quantity of dilution water is limiting, it can be minimized by using effluent with a near-zero nitrate concentration to dilute the concentrated feed solution; this recycle mode would also reduce the amount of treated effluent to be discharged. Recycle ratios of 9:1 have been operated successfully in development work. One disadvantage of this mode of operation is that any unreacted component such as the major cation (Na^+ or NH_4^+) will be present at the same concentration as in the concentrated feed. The denitrifying bacteria will grow satisfactorily in the presence of Na^+ and NH_4^+ to 1 M concentration; therefore, the nitrate content of the concentrated feed cannot exceed $\sim 70,000$ g/m³ (7% NO_3^-). With other minor impurities, care must be taken to prevent buildup to a toxic level. The C:N ratio must also be monitored closely because any unused organic carbon is recycled to the bioreactor. If this recycled carbon is not considered, the C:N ratio may become too high. In many instances, however, the extra care required by this mode of operation will be more than compensated for by the reduction in dilution water requirements.

The selection of a particular mode of operation depends on feed concentrations, feed rate, building size, pumping cost, and substrate processing cost. All these factors must be considered to allow the optimum flowsheet to be chosen for the specific wastewater application.

2.3 Effluent Attainable

The biological denitrification process is an efficient method for destroying nitrates. It must be realized that, although nitrate discharge can be reduced to very low levels, the process produces small quantities of organic carbon that may require posttreatment. Conventional sanitary wastewater treatment is effective in reducing any excess biological oxygen demand (BOD).

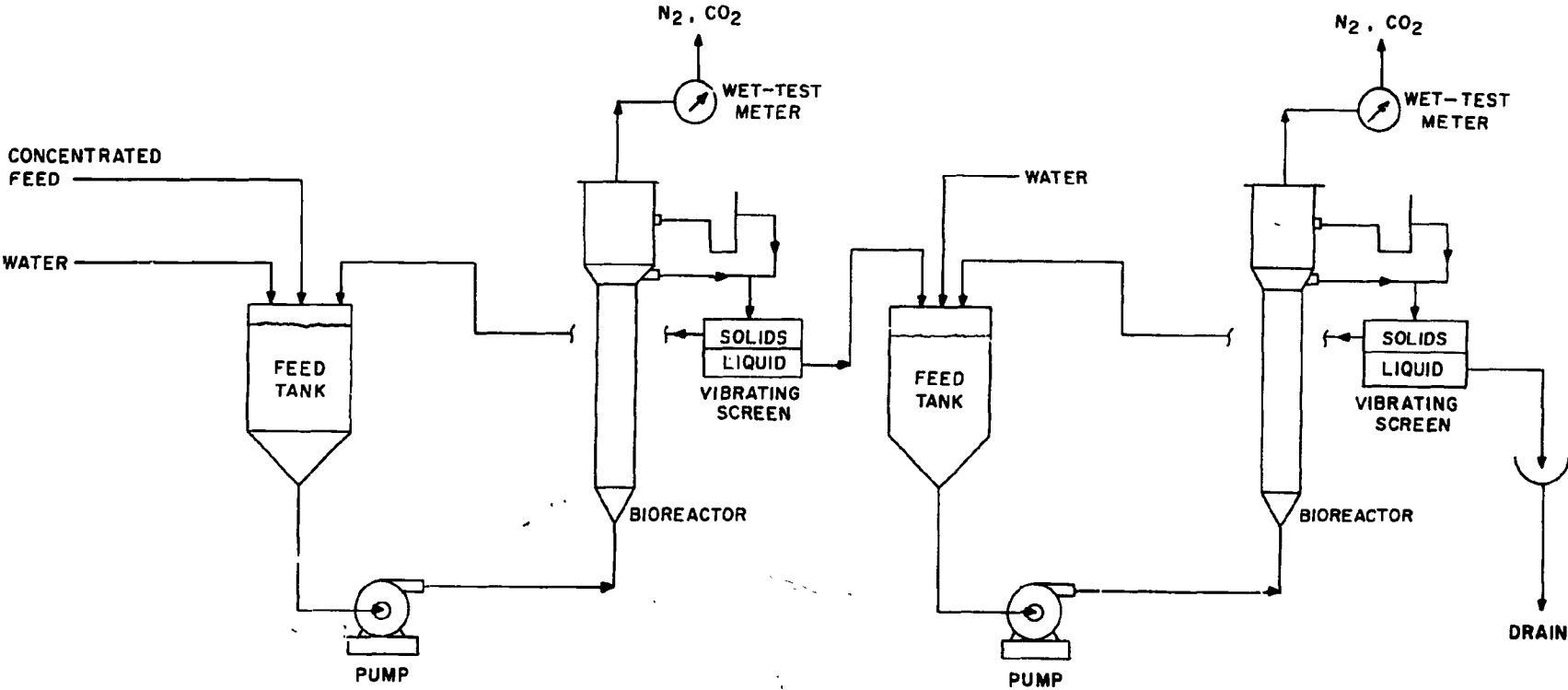


Fig. 3. Biological denitrification flowsheet for two bioreactors in series.

2.3.1 Nitrate effluent

A very low level nitrate discharge (<1 ppm) is obtainable with the fluidized-bed, biological denitrification system. The plug-flow characteristics of the fluidized bed allow these low levels of nitrate to be achieved in practical bioreactor lengths.

2.3.2 Carbon effluent

By-products of biological denitrification are present in the effluent from the system. The effluent contains the following carbon sources: (1) biomass, (2) soluble organic biomass degradation products, (3) excess organic feed nutrient, and (4) dissolved carbon dioxide. Typical levels of organic carbon and biomass distribution in a 0.10-m-ID bioreactor are shown in Table 3. The organic carbon concentration of the effluent can be reduced to required levels using standard, available sanitary wastewater treatment. Removal of the filterable biomass is one possible solution, but since it is a minor component of the carbon discharge problem, we chose to treat the entire mixed-effluent stream.⁷ A large component of the carbon effluent can be reduced by carefully adjusting the organic feed nutrient added to the feed. Although some excess is necessary for complete denitrification, it can be minimal.

3. PROCESS DESIGN

3.1 Bioreactor

The bioreactor is the vital part of the fluidized-bed denitrification process. The configuration of the bioreactor is important in its overall performance of the denitrification system. The fluidized-bed bioreactor performance is characteristic of ideal plug-flow reactors and can be determined using standard design equations in conjunction with developed kinetic expressions.

Table 3. Typical organic carbon levels^a

| Stream | Carbon type | Carbon concn. (g/m ³) | Carbon quantity (g/d) |
|-----------------------------|--|--------------------------------------|--------------------------|
| Feed | ETOH ^b | 200 | 1150 |
| Effluent | Soluble | 25 | 160 |
| | ETOH | 40 | 240 |
| | Biomass | 20 | 130 |
| | Dissolved CO ₂ | 100 | 660 |
| Total | | | 1190 |
| Bioreactor | 0.10-m-ID by 6-m bioreactor contained 20 L of settled solids at 5% biomass loading = 1600 g carbon | | |
| To biomass control system | Attached biomass (50% of bioreactor/d) | | 950 |
| From biomass control system | Unattached biomass | | 330 |

^a Feed concentration test, 500 g/m³ NO₃⁻.

^b ETOH = ethanol.

3.1.1 Configuration

Two bioreactor geometries have been used in R&D studies. Both bioreactors, the fully tapered (inverted, truncated cone) and the cylindrical with a tapered top section, produce a very stable fluidized bed. Since the cylindrical bioreactor with the tapered top is simpler to construct, it is the recommended geometry for tall reactors. This geometry has been used for 0.05-, 0.10-, 0.20-, and 0.50-m-diam bioreactors with excellent results.

The tapered section of the bioreactor allows the fluidized bed to expand and remain stable over a wider range of flows. One end of the tapered section has the same diameter as the cylindrical portion of the bioreactor, and the larger end has a diameter 1.75 to 2 times larger than the cylindrical portion. In this tapered section, the cross-sectional area for flow is increased three- to fourfold; therefore, the linear velocity of the liquid is decreased, allowing solids to disengage from the liquid flow. This disengaging section should make a 5 to 8° angle

with the vertical. A cylindrical top section 0.1 m long is used above the tapered section for liquid outlet and gas-liquid separation. Figure 4 shows a typical bioreactor configuration.

A relatively clear overflow is necessary to maintain the desired biomass loading. If an excess of particles is cycled to the biomass control system via the liquid overflow, the biomass loading cannot be controlled and may fall below the desired level. Particle carryover in the liquid overflow is particularly troublesome in a bioreactor operating at a high concentration of nitrate ($>8000 \text{ g/m}^3$). The high gas flow rate in these bioreactor systems inhibits the settling of particles in the tapered section. Therefore, with high-nitrate systems, a tapered section with an outlet diameter (D_2) that is twice the inlet diameter (D_1) is recommended.

Adequate feed distribution at the inlet of the bioreactor is necessary for full utilization of the entrance section. A single feed-entry point at the center of the conical bioreactor bottom was used with the 0.05-, 0.10-, and 0.20-m-diam development bioreactors. This single-entry-point method produced bed channeling in the entrance section of the 0.50-m-diam bioreactor; therefore, an array of five equally spaced feed-entry points was used. The multiple-entry-point method provided a homogeneous bed in the entrance section of the bioreactor and would be the recommended method for feed distribution in larger ($>0.20\text{-m-diam}$) bioreactors.

A buildup of excess biomass on the interior surfaces of the bioreactor can cause channeling or clogging of the bed. The introduction of air or nitrogen gas in the bottom of bioreactor is an effective means for dislodging a portion of the biomass buildup; however, a manhole access in the top of the bioreactor is recommended to facilitate periodic direct cleaning. Because dried biomass tends to form at the gas-liquid interface in the top of the bioreactor, a liquid mixer in the top of the bioreactor is recommended to prevent any buildup.

3.1.2 Sizing

Biodenitrification projects performed at ORNL have used several fluidized-bed bioreactors of varying diameters (0.05 to 0.50 m) and lengths (1 to 7 m). Experimental evidence has shown that the volume required for these bioreactors can be estimated by assuming that flow

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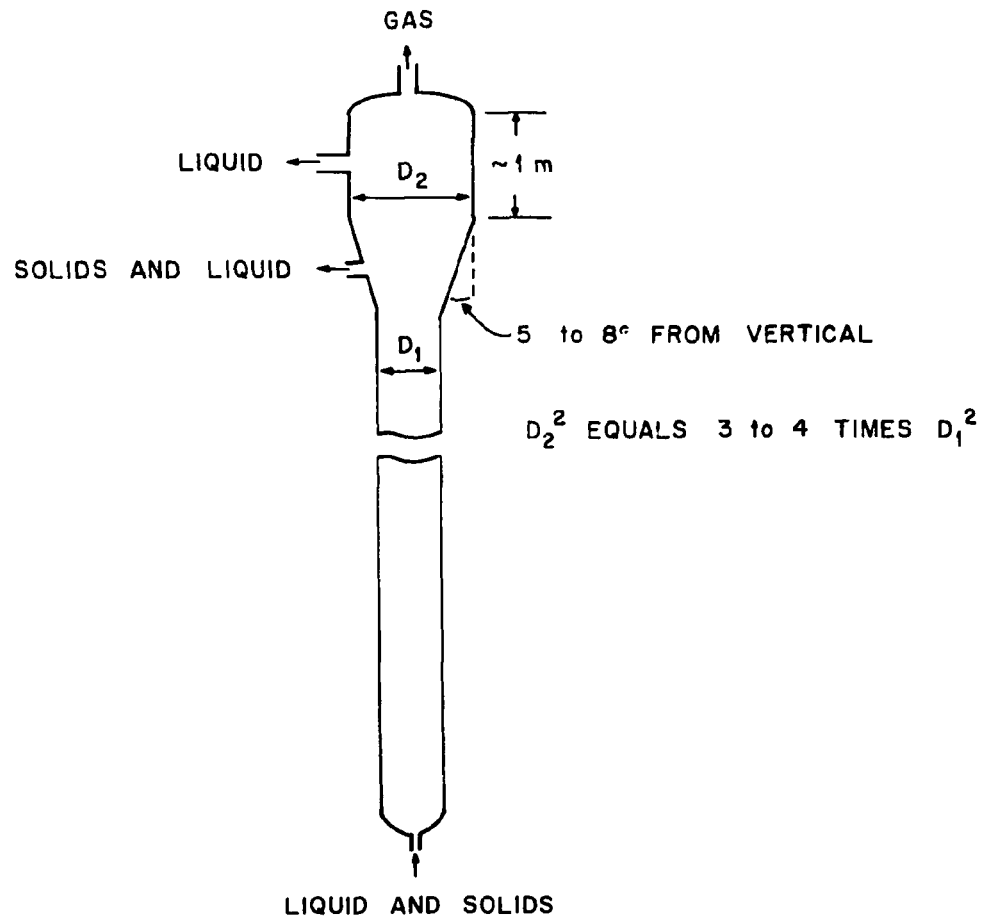


Fig. 4. Bioreactor configuration.

in the bioreactor behaves according to plug-flow models. Thus, the required hydraulic residence time (or space time), τ , can be calculated from the following familiar design equation:

$$\tau = - \int_{C_{\text{NO}_3^-,f}}^{C_{\text{NO}_3^-,e}} \frac{dC_{\text{NO}_3^-}}{-r_{\text{NO}_3^-}},$$

where $C_{\text{NO}_3^-,e}$, $C_{\text{NO}_3^-,f}$, and $r_{\text{NO}_3^-}$ represent the concentration of nitrate in the effluent, the concentration of nitrate in the feed, and the rate of denitrification respectively. This equation can be solved for τ if the denitrification kinetics are known and the feed and effluent nitrate concentrations are specified.

At low average nitrate concentrations (average between reactor inlet and effluent nitrate concentrations), a logarithmic model has been used to correlate and investigate the dependence of rate on average nitrate concentrations.

The expression

$$r_{\text{NO}_3^-} = a + b \ln C_{\text{NO}_3^-},$$

where a and b are experimentally determined constants, $r_{\text{NO}_3^-}$ is given in $\text{kg NO}_3^- (\text{N})/\text{d}\cdot\text{m}^3$, and $C_{\text{NO}_3^-}$ is the average nitrate concentration in g/m^3 , provides a description of the bi-denitrification kinetics which occurred in the 0.50-m-diam column up to an average nitrate concentration of $700 \text{ g}/\text{m}^3$. Using a method of least squares, values of -66.81 and 15.23 were obtained for a and b , respectively, with a correlation coefficient of 0.78 from 36 d (36 determinates) of operation below average nitrate concentrations of $700 \text{ g}/\text{m}^3$. This rate expression can be combined with the design equation above, numerically integrated, and used to predict the hydraulic residence time required under varying nitrate loadings.

Above average nitrate concentrations of $700 \text{ g}/\text{m}^3$ there appears to be no statistical relationship between the average nitrate concentration and the denitrification rate. For the 22 d (22 determinates) in which

the 50-cm-diam bioreactor operated with an average nitrate concentration greater than 700 g/m^3 , the denitrification rate ranged from 22 to 48 $\text{kg NO}_3^- (\text{N})/\text{d}\cdot\text{m}^3$ with a mean denitrification rate of $32.7 \pm 7.7 \text{ kg NO}_3^- (\text{N})/\text{d}\cdot\text{m}^3$.

Although this model has been used in preliminary data evaluations, other models are being investigated at ORNL. If the model described above is used, the parameters should be evaluated under operating conditions established for a particular application and with consideration for site-specific variables.

Using the relationship

$$V = \tau \cdot Q ,$$

where V and Q are the reactor volume and the volumetric flow rate to be processed, respectively, the essential volume of the reactor can be defined. The diameter to be used in generating the required volume is calculated from the relationship

$$v = Q/A = Q/(\pi D^2/4) ,$$

where v is the superficial liquid velocity in the column, and A and D are the column cross-sectional area and diameter respectively. Values of v are chosen to provide at least a minimum fluidization of the column and yet avoid washout of the bacteria-coated support particles. When using anthracite coal particles in the -30+60-mesh size range, ORNL has found that a value of v of 0.84 cm/s satisfies the above requirements.

This approach to specifying the diameter can be used since the rate of denitrification is independent of the column diameter in the range of diameters studied. This independence, which is indicated in Fig. 5 for 0.05- and 0.10-m-diam columns, has also been verified in 0.20- and 0.50-m-diam columns.

After the volume and diameter of the cylindrical geometry have been specified, the length is determined. The required length can be divided between two or more reactors if the total length is impractical for use in a single reactor.

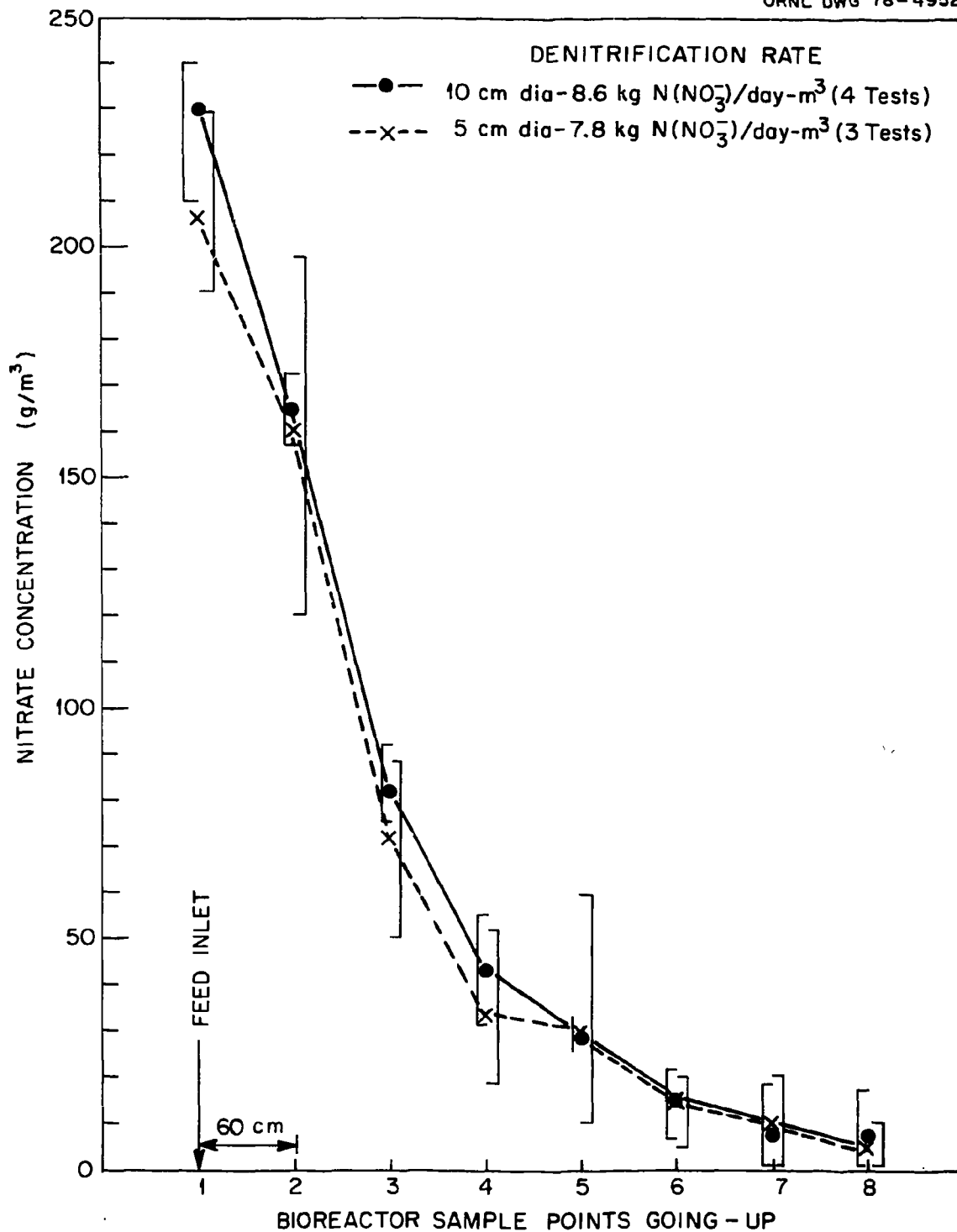


Fig. 5. Effect of column diameter on denitrification rate.

The above procedures were developed after analyses of data obtained under the following operating conditions:

Feed nitrate
concentrations: 0 to 10,000 g/m³
Feed pH: 7.0 (average)
Feed temperature: 28 to 32°C
Biomass loading: 15% dry weight of coal.

3.2 Biomass Control

The biomass control system is essential to the proper operation of the fluidized-bed bioreactor. Vibrating screen filters are used to remove excess biomass from the fluidized particles to prevent overgrowth of biomass. Pilot-plant studies have yielded a method for sizing vibrating screens for this application.

3.2.1 System description

As discussed in Sect. 3.1, the denitrification reaction produces biomass. The excess biomass generated in the denitrification reaction must be removed periodically for stable bioreactor operation. The amount of biomass to be removed is theoretically 0.1 g per g of NO₃⁻ decomposed. Operating experience has indicated that a biomass loading of no more than 10 to 20% dry weight is satisfactory. Overgrowth of a biomass has the following detrimental effects on the reactor operation:

1. The reactive surface area and, in turn, the denitrification rate are reduced.
2. Nitrogen gas that is formed during the denitrification reaction can be trapped, causing the particles to float and wash out of the bioreactor.
3. Particles tend to become sticky, which makes fluidization difficult.

To prevent overgrowth, a side stream of liquid and bacteria-covered coal particles is removed from the tapered section of the bioreactor. The particles with an overgrowth of biomass are less dense, causing the particles to migrate to the top of the fluidized bed for removal in the side stream. This side stream and the clear liquid effluent from the

bioreactor flow by gravity to a vibrating screen equipped with a 30-mesh (0.50-mm-diam) screen. The vibrating action of the screen removes excess biomass from the substrate. The "clean" particles (coal) remain on top of the screen and are sludged at the screen outlet with the feed stream or process water for transfer to the feed tank of the bioreactor from which the particles were removed. Using this method, the particles remain in the same bioreactor circuit. Liquid and biomass that pass through the 30-mesh screen flow to the next bioreactor in series or to posttreatment.

3.2.2 Equipment sizing

The essential part of the biomass control system is the vibrating screen. The screen processes liquid that contains 5 to 15% of the particles to which bacteria have adhered. The liquid flows to the screen by gravity and is controlled by an on-off valve and by adding clean particles to the system to increase the height of the bed. If the analytical results show a high biomass loading, the valve can be opened to circulate particles through the screen to decrease the biomass loading. If the top of the fluidized bed is below the particle take-off point, particles cannot be processed. In this case, fresh particles are added to the bioreactor feed to increase the height of the fluidized bed and allow circulation of biomass-covered particles. Coal particles used in development work were added batchwise at an average rate of 5% of the bioreactor loading per week. This large rate was due to the breakage of coal particles; however, if a more durable support material is used, the rate of addition would be lower.

In development tests, 24-in. (0.6-m) vibrating screens were used for biomass control with 6-m-long fluidized beds. Based on the total flow rate of the bioreactor, the upper limit of 48 L/min was established for the 24-in. screens. Table 4 gives scale-up factors suggested by the manufacturer* of SWECO vibrating screens.

* SWECO, Inc., 6033 East Bandini Blvd., P. O. Box 4151, Los Angeles, Calif. 90051.

Table 4. Scale-up factor for SWECO vibrating screen

| Flow rate scale-up factor | Screen size (in.) |
|---------------------------|-------------------|
| 1 | 18 |
| 2 | 24 |
| 4 | 30 |
| 10 | 48 |
| 17 | 60 |
| 24 | 72 |

The scale-up factor, x , for a given biomass control system is:

$$x = 2 \left(\frac{\text{Bioreactor feed rate (L/min)}}{48 \text{ L/min}} \right) .$$

Given the scale-up factor, the screen size can be read from Table 4. This method is for fluidized beds ≤ 6 m long. Taller bioreactors may require larger screens because of the larger volume of biomass at a given bioreactor flow rate; this is also an upper limit on throughput and for effective operation of oversized screens.

Vibrating screen failures have been routine in this service. A complete supply of spare parts is recommended if continued operation is to be maintained.

3.3 Support Systems

Several support systems are required for a biological denitrification facility, such as sampling and analysis of samples to measure the performance of the system and instrumentation to monitor and control important variables (e.g. pH, flow rates, and liquid levels). The facility requires the usual utilities and also equipment for cold storage of bacteria.

3.3.1 Sampling and analysis

Liquid sample ports should be provided at least at the inlet and outlet of each bioreactor so that performance can be measured. Because these sample ports will become clogged with bacteria, the sampler must be equipped with a water or air back-flush system for routine cleaning. Other sampling ports along the length of the bioreactor would be useful in troubleshooting and determining reactor profiles.

Facilities should be available for analyzing the liquid sample for TOC, BOD, nitrate, nitrite, PO_4^{3-} , and trace metal nutrients. The frequency of sampling and the specific determinations required for each sample depend on the operation of the system. Although grab samples have been adequate during the development of this process, on-line continuous monitoring of liquid stream constituents would be desirable.

Solids sampling is required so that the biomass loading on the particles can be determined. Again, sampling devices should have provisions for routine back-flushing to remove biomass. Solids samples can be taken at the same locations as liquid samples. These samples should be analyzed for biomass loading using the procedure given in the Appendix.

3.3.2 Instrumentation and controls

The flow rate to the bioreactor must be sensed and controlled. This stream contains solids particles and biomass. Development work has shown the magnetic flow meter to be very reliable in sensing flow rates in the solids-containing stream. A control valve that is reliable over the flow range and with solids in the liquid stream is needed on the feed stream.

Liquid-level control is needed in the bioreactor feed tank so that flow is maintained in the bioreactor. Bubbler-type liquid elements have been successfully used in development work for level sensing. A control valve on the makeup stream is used to control the level in the tank. The gas (CO_2 , N_2) evolved from the system is a continuous indication of the bioreactor performance. A decrease in the gas evolution rate indicates a problem, and other analyses may be required to troubleshoot the problem. Wet-test meters have to be used successfully in development so that this gas flow rate can be measured. Figure 6 is a control diagram for a typical dual bioreactor system.

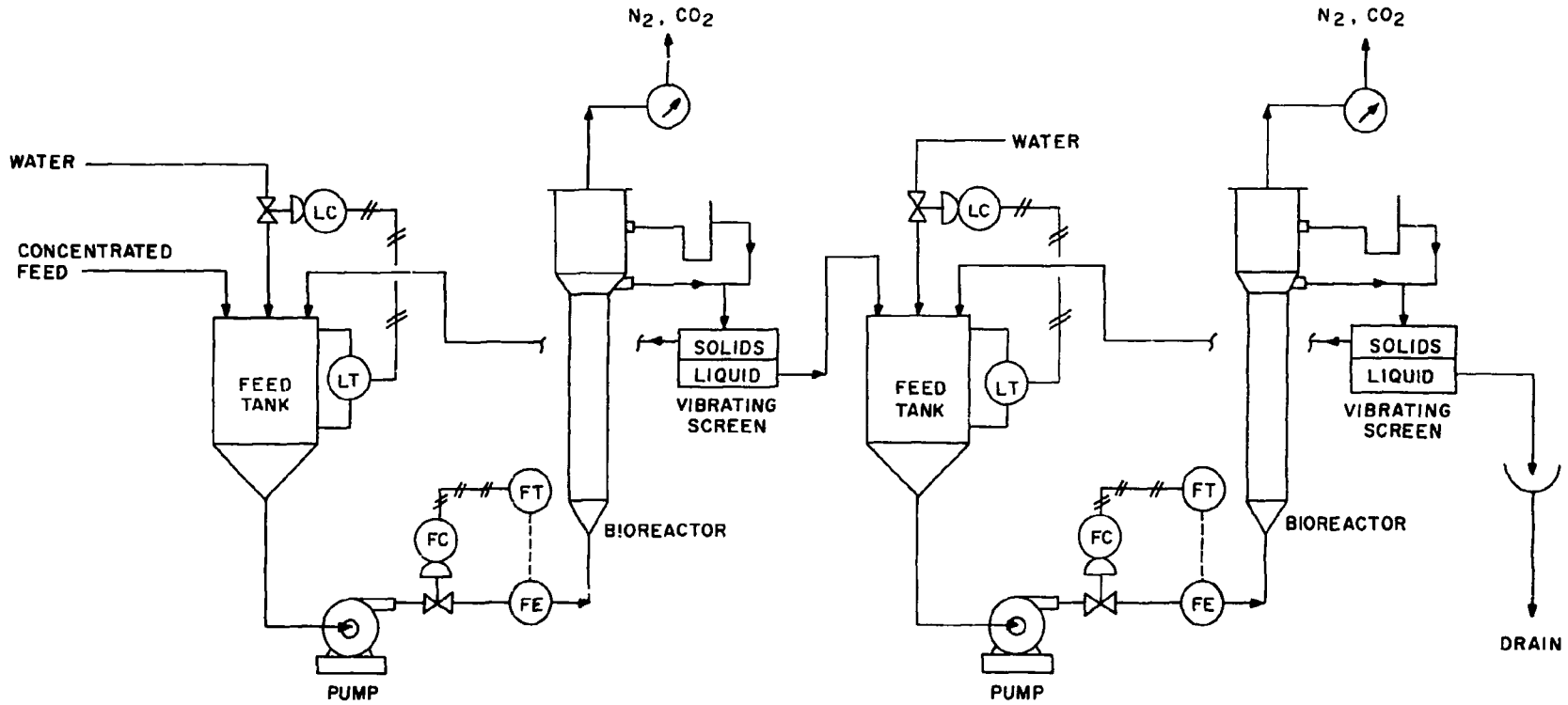


Fig. 6. Biological denitrification control diagram.

The pH and temperature are continuously monitored at the inlet of each bioreactor. The temperature is controlled by injecting steam into the process water that is added to the feed tank of the first bioreactor. The pH of the feed stream should be adjusted prior to entering the system; however, as denitrification occurs, the pH increases. Because of this increase in pH, bioreactors operated in series may require intermediate adjustment to maintain the pH in the optimum range of 7.0 to 7.5.

3.3.3 Utilities

Standard process utilities are required. These include process air for instrumentation, electricity for illumination, a pump, and vibrating screens. Compressed air and nitrogen are helpful for blowing out lines and dislodging bacterial growth. Process water and drains are needed for flushing and cleanup operation.

3.3.4 Bacteria storage

Bacteria should be maintained for seeding the bioreactor. It is recommended that facilities be available for storage (at -40°C) of a small frozen stock of bacteria. A cold room (1 to 3°C) is required for storage of larger quantities of bacteria, which provide rapid reseedling of the bioreactor, and for storage of the bioreactor contents during long-term shutdown. Procedures for long-term shutdown are given in the following section.

4. PROCESS OPERATION

4.1 Startup Procedure

The bacteria used in the startup of the fluidized-bed denitrification bioreactor were taken from frozen stock that had been prepared for starting the Y-12 Plant denitrification reactors. These bacteria had been grown in 0.21-m^3 (55-gal) drums that were open to contamination, and are almost certainly a mixed population. The bacteria are jetted into the bioreactor along with -30+60-mesh coal particles. The bioreactor is initially fed at a nitrate concentration of 1000 ppm, and it

is recycled until the nitrate concentration of the bioreactor effluent is ~ 500 ppm. This recycling allows the bacteria to attach to the -30+60-mesh coal particles in the fluidized bioreactor. The operating temperature is maintained in the 28 to 32°C range, and the pH entering the bioreactor is ~ 7.0 .

4.2 Steady-State Operation

After the recycling feed concentration has been reduced from 1000 to 500 ppm, a continuous feed may be initiated and the process operated at steady state.

The operator selects a desired inlet or outlet nitrate concentration and adjusts the feed rate to get the desired concentration. Samples are taken at the process inlet and outlet daily. Additional samples are taken as needed along the bioreactor length. These samples are analyzed for nitrate, nitrite, carbon, and pH to determine any problems and to make the appropriate adjustments to the process.

To operate the system at steady state, controllers are used to maintain the temperature, pH, and flow rates. The temperature can be maintained at ~ 28 to 32°C by injecting steam into the process water and mixing the heated process water with the concentrated feed. The pH of the bioreactor feed is maintained at 7.0. When operating two bioreactors in series, it may be desirable to readjust the effluent of the first bioreactor to pH 7.0 before it enters the second bioreactor.

4.3 Shutdown Procedure

4.3.1 Temporary

For periods of ≤ 30 d, the process can be shut down with feed and solids remaining in the bioreactor.

4.3.2 Long term

For periods of shutdown longer than 30 d, it is necessary to remove the bacteria-covered solids from the bioreactor and store it in a 1000-ppm nitrate solution at a reduced temperature; for 60 d, 4°C will be sufficient, but for longer periods the bacteria must be frozen at -10°C or lower. After shutdown, the reactors and feed tanks should be washed with caustic to remove any remaining bacteria.

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6. APPENDIX: METHOD FOR DETERMINING BIOMASS LOADING

The following procedure is used for determining the biomass loading:

1. Take solids sample.
2. Dry sample at 105°C.
3. Cool sample at room temperature.
4. Weigh sample (W_1).
5. Wash sample with 6 M NaOH to remove bacteria.
6. Wash sample with water.
7. Dry sample at 105°C.
8. Cool sample at room temperature.
9. Weigh sample (W_2).
10. Calculate biomass loading using the following formula:

$$\text{Biomass loading} = \frac{W_1 - W_2}{W_1} \times 100.$$