0273-2289/90/2425—0627$02.00

Bioreactor Development with Respect to Process Constraints Imposed by Bio-Oxidation and Waste Remediation

Scientific Note

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Index Entries: Bioreactor; bioremediation; bioleaching; hazardous waste; mineral processing.

INTRODUCTION

A great deal has been publicized about the industrial promise of biotechnology. To date, however, major technological impacts have mainly been in the pharmaceutical and health care industries. Process conditions encountered in these industries are significantly different from those common to the fuels, chemicals, minerals, or environmental area. In order to develop bioprocess applications in these areas, the proper equipment must be available that will perform in the industrial setting.

The focal point of an industrial bioprocess is the bioreactor, the equipment in which an economically attractive, biologically-assisted chemical transformation is accomplished. Biological reactors have inherited many of the features of conventional chemical reactors; however, bioreactor analysis and design involves an interplay of a multitude of disciplines. Not only must biochemical engineers ensure that the appropriate chemical reactions are occurring, but they must also make certain that the bioreactor system supports the growth, reproduction, and metabolic activity of the biological components (cells or whole organisms) responsible for the chemical changes.

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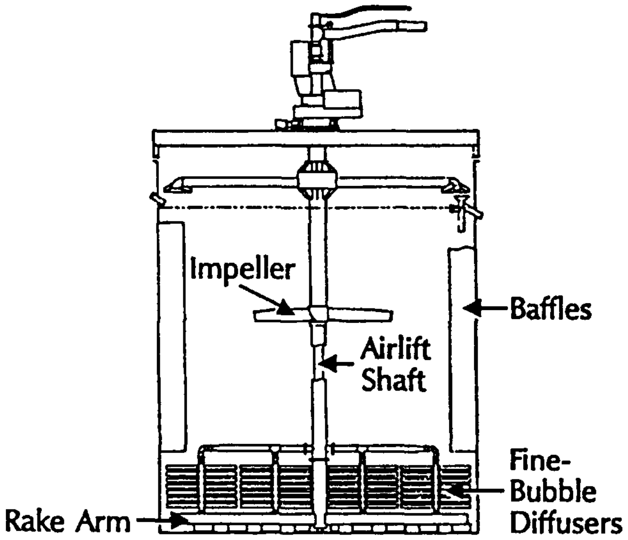

Fig. 1. EIMCO bioreactor details.

A study done by the National Research Council, National Commission on Engineering and Technical Systems, in 1986 (*1*) recognized a need for the development of improved industrial bioreactor systems. Problems with heat exchange and oxygen transfer were identified. The study also cited a need to understand the mixing patterns in large vessels and to develop a rational basis for design and scale-up. Development of a fundamental understanding of the gas–liquid flow patterns, heat transfer in two-phase flow, and macro- and micromixing were considered key items.

These issues, and many others, have been addressed during the development of an innovative bioreactor by EIMCO PEC to meet the process demands of biologically-activated oxidation of refractory precious metal ores in which gold and silver are finely dispersed in sulfide minerals (bioleaching) and hazardous waste biodegradation (bioremediation).

EIMCO BIOREACTOR DETAILS

The EIMCO bioreactor is basically a modified slurry agitator that uses a thickener drive and rake arms and employs a diffuser-based aeration system. The reactor is constructed of materials that can withstand the strong oxidative environment and are not toxic to the microorganisms. The reactor is illustrated in Fig. 1.

Fine bubble aeration is accomplished by passing air through flexible membrane diffusers mounted on the rotating rake arms. This also provides considerable turbulence for mixing purposes. In a hazardous waste application, the elastomeric diffuser membrane material must be chemically resistant to the organic contaminants undergoing biodegradation. In bioleaching applications, the diffuser material is selected to withstand the abrasive nature of the bio-oxidation slurry. Solids that settle on the bottom of the tank are raked to the center, where an airlift pumps them back to the top for resuspension.

The tank is baffled to enhance mixing, and when increased turbulence is required, an impeller is mounted on the airlift shaft to provide additional mixing. In that situation, the aeration system is separated from the independent mechanical mixing system. The reactor has an automatic temperature control feature and can be equipped with a variable speed drive.

Depending on the application, any number of reactors are arranged in a cascading system to permit continuous feed and overflow. The reactor system is designed for steady-state continuous operation. With this design, the maximum biokinetic rate is achieved.

Two pilot plants are operating in EIMCO's Salt Lake City laboratory. The bioleaching plant consits of three stages. Two first stage 60-L reactors, in parallel, are followed by a second and a third stage 60-L reactor connected in series. The hazardous waste bioremediation plant consists of three 60-L reactors connected in series.

In addition, both laboratory bench-scale equipment and field pilot units with slightly different designs have been constructed. The bench-scale unit, consisting of three cascading 10-L bioreactors, has been designed to allow continuous operation on a relatively small scale and minimizes operator attendance.

Two bioreactors, with a combined vol of 112 m^3, have been operated for an extended time period. These bio-oxidation units processed a refractory arsenopyrite concentrate.

IMPACT OF BIOPROCESS REQUIREMENTS ON BIOREACTOR DESIGN

It is usually desirable to operate a reactor close to its optimum capacity. This is often constrained by mass or heat transfer considerations. Design and operation of a continuous bioprocessing circuit requires innovative engineering to overcome limitations, yet still work within the biological boundaries. In order to engineer the equipment to meet industrial requirements, the bioprocess must be well defined.

Bio-Oxidation of Refractory Ores and Concentrates (Bioleaching)

The direct bacterial leaching of sulfide minerals only recently has been considered as an alternative hydrometallurgical process although heap leaching has been practiced for many years. About five years ago,

Table 1
Operating Parameters

Parameter	Range/Requirement
Sulfide content	3–42%
Temperature	32–40°C
Pulp density	10–30% solids
Oxygen demand	Exceed critical oxygen concentration
Reactor residence time	>Bacteria reproductive cycle (estimated to be 12–20 h)
pH	1.2–1.8
Nutrients	K, Mg, N, P, and CO_2 (carbon source)

research was begun at EIMCO to develop a bioreactor capable of handling the bio-oxidation of refractory gold and silver ores and concentrates on a continuous basis.

The EIMCO Bioleach process utilizes naturally-occurring microorganisms that oxidize pyrite and arsenopyrite as part of normal metabolism. Bacterial leaching refers to the role of bacteria, primarily *Thiobacillus ferrooxidans,* but also *Leptospirrillum ferrooxidans,* and other species of *Thiobacillus* in the solubilization of minerals. These bacteria thrive in an aerobic, acidic, inorganic environment, and derive energy from the oxidation of reduced inorganic sulfur compounds and ferrous iron. During this bacterial activity, gold or silver loses its refractory nature as a result of the solubilization of these compounds.

To accommodate the bacterial process, the bioreactor was designed to maintain a healthy and prolific culture of bacteria and allow control of the process environment. Design parameters were defined, and both throughput rate and energy requirement of the overall bio-oxidation were focused upon.

Certain parameters were found to be critical, and the bioreactor operates within fairly specific ranges. These parameters are listed in Table 1. Other issues that had to be considered during the initial design phase included the potential shear sensitivity of the bacteria, the possibility of toxic effects owing to different materials of construction, and the differences that would arise during the processing of ores rather than high grade sulfide concentrates.

Bioremediation

Many of the organic substances included within the Environmental Protection Agency's (EPA) hazardous waste list are biodegradable. Organisms have been found at most Superfund sites that biodegrade these wastes when the proper amount of oxygen and other nutrients are present and the environmental conditions, such as pH and temperature, are favorable.

Biodegradation in nature of many of these compounds often occurs very slowly owing to limited aeration and nutrient availability. However, process kinetics can be accelerated substantially through the use of properly designed equipment (i.e., vessel treatment). During the past year, EIMCO has modified their bioreactor for use in certain hazardous waste remediation applications.

Processes that treat organic sludges and contaminated soils by extracting the organics into an aqueous phase and biologically degrading them fit into a liquid/solid system category. Most existing systems have been based upon aerobic digester technology, where extraction and biodegradation is accomplished in single or multilple reactor vessels operated in a batch mode. These vessels have been open lagoons, lined ponds, and concrete or steel tanks. Existing systems required significant energy input to keep solids suspended, provide adequate mixing, and maximize desorption of the organics from the solid particle to the aqueous phase.

The EIMCO approach allows suspension of solids and meets aeration and mixing needs at the higher solids concentrations and at a lower energy input. Solids concentrations are typically in the 20–40 wt% range, and energy requirements of the pilot units are 25–50% of those encountered in conventional mixing technology. A turbine mixer requires between 0.4–0.8 kWh/m^3 under these process conditions.

A system using up to four reactors is arranged in a cascading system and operated in a continuous feed/overflow mode. By providing the optimum conditions for bioactivity, biodegradation of the toxic organic substances is maximized.

Additionally, since most soil or sludges containing organic substances will release volatile compounds when large amounts of air are diffused into the compounds, these reactors are gas-sealed, and these compounds (often biodegradable) are recirculated back into the slurry through the diffuser. This feature also allows operation in an anaerobic mode using inert gases, such as nitrogen, for slurry mixing. Oxygen and carbon dioxide in the exhaust gases are monitored with gas analyzers and adjusted to ambient conditions, as required. A full scale transportable unit has been designed. This unit is 3.7 m in diameter by 7.5 m in height and will be skid mounted to allow transportation of the unit from site to site.

Bio-Oxidation and Bioremediation Process Flowsheets

A typical EIMCO Bioleach flowsheet requires a collection of equipment specially designed to handle the process requirements of biologically activated oxidation of mineral solids. The heart of the system is comprised of several EIMCO Bioreactors connected in series, supported by associated solids/liquid separation and handling equipment. Residue solids obtained from biological oxidation of a refractory ore or concentrate are sent through

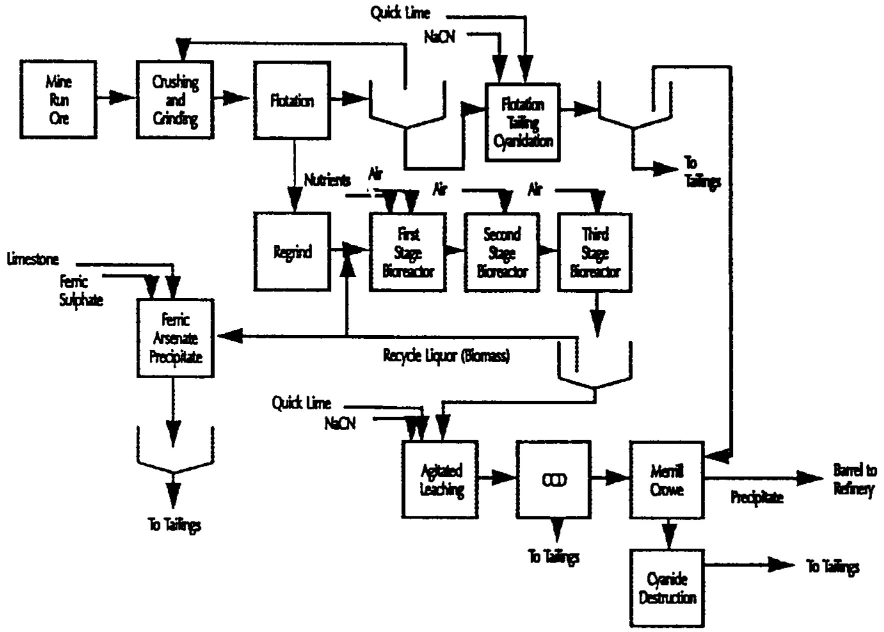

Fig. 2. Example of a bio-oxidation flowsheet.

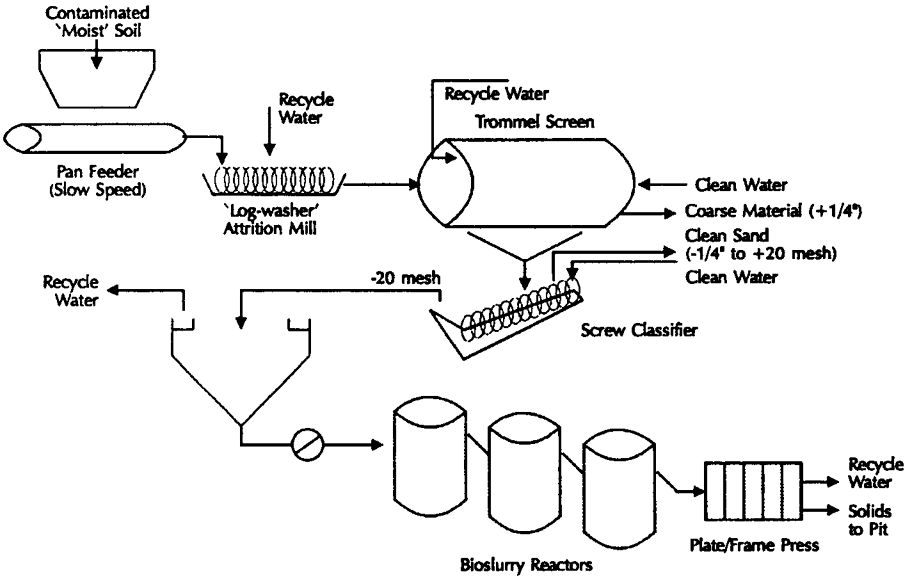

Fig. 3. Example of a bioremediation flowsheet.

a conventional cyanide leach circuit (Merrill-Crowe, Carbon-in-Pulp, Carbon-in-Leach) to extract the gold or silver. The bioleach process flowsheet for a typical concentrate is outlined in Fig. 2. Figure 3 illustrates a bioremediation flowsheet where soil is excavated, slurried, screened, and washed, and the fine particle fraction is sent through the bioslurry reactor train.

BIOREACTOR SCALE-UP ISSUES

Significant differences exist between large scale systems and laboratory prototypes. Scale-up has been defined as the transition from *procedure*—an established way of doing things—to *process*, a series of operations leading to a specific end, such as manufacturing of a product (2). Three areas that have a significant impact during the transition from the EIMCO laboratory bioreactor to a full size system are oxygen transfer, heat balance, and mixing requirements. These variables are highly interdependent and must be optimized on a reasonably large scale for proper plant design.

Oxygen Transfer

Techniques have been established to measure how well an existing bioreactor system is transferring oxygen. Actually determining how changes in bioreactor design parameters will affect oxygen transfer, and what will happen during scale-up, is a complex problem complicated by the growth cycle of the bacteria.

Aeration rate is defined as the absolute amount of oxygen available to transfer into the system. The scale-up approach being used by EIMCO involves holding the overall mass transfer coefficient (K_La) for oxygen constant as the system enlarges and addressing the following:

1. Aeration device: Fine bubble diffusers employing highly efficient fine bubble air diffusion mechanisms were specially designed for this bioreactor.
2. Solution properties: It was recognized that some biological systems, such as in bioleaching, contain surfactants and high concentrations of ionic solutes. This results in reduced bubble coalescence, reduction of the average bubble size diameter, an increase in the interfacial area for oxygen transfer, and enhanced oxygen transfer, even at the larger scale.
3. Mixing patterns: The gas introduced for oxygen transfer purposes in a large reactor usually does not encounter the same degree of mixing as in the smaller systems. In order to maintain adequate oxygen transfer, the occurrence of poorly-mixed zones as the system scales up must be avoided.
4. Biological growth patterns: When the oxygen transfer ability of the equipment is exceeded by the ability of the organisms to consume oxygen, the biological side suffers and production will be limited. The EIMCO system minimizes the cycling pattern that can be encountered with biological systems and achieves a more representative steady-state operation.
5. Surface aeration: It is considered negligible for large scale bioleaching bioreactors and not applicable for bioremediation.

Table 2
Heat Transfer Considerations During Scale-Up

Source	Impact
Microbial growth	As the microorganisms multiply, the total energy requirements of the cells in the system increases, causing increased heat generation (3). For a wide variety of organisms, heat evolution is a linear function of oxygen consumption. On a small scale this could be negligible, but probably not on the larger scale.
Heats of reaction	In the bioleaching application, oxidation of sulfide mineral concentrates is exothermic and heat is released for every gram of sulfide oxidized to sulfate.
Agitation system	In small tank reactors (conventional), the heat input, owing to agitation, can contribute as much as 30% of the maximum heat load (3). This must be quantified for each innovative bioreactor approach.
Evaporation	Heat loss owing to evaporation may be significant as the surface area of the reactor and the air flow to the system increases.
Air stream	Sensible heat of the incoming airstream may impact the small size reactors significantly. Oxygen transfer is less efficient at shallow depths resulting in higher air flows through the smaller reactors.
Environmental	Estimates must be made to handle expected extremes in ambient temperatures and losses owing to convection.

Heat Balance

As the EIMCO bioreactor is scaled up, the ratio between reactor volume and surface area changes. In order to determine the heating and cooling requirements of the full size unit and design for the system to operate within the designed temperature range, the sources of possible heat loss or gain had to be identified and the impact on the system assessed. These are listed in Table 2.

Mixing Requirements

As the EIMCO bioreactor is scaled up, the problem of effective mixing in the presence of large quantities of air and maintaining the suspension of coarse particles becomes significant. A small pilot-scale bioreactor designed to perform a particular plant-scale process that requires significant mixing is not a good model for the full scale equipment. This is because pumping capacity and the maximum impeller zone shear rate are two high, and the blend time is too short in the smaller reactor.

For scale-up purposes, the approach employed by EIMCO involves use of experimental data to provide an estimation of the controlling process steps. Pilot-plant experiments are underway involving both the innovative EIMCO reactor and a conventional turbine mixed reactor. Information obtained has allowed identification of appropriate mixing parameters relating to the rate controlling steps. Power input to the pilot plant experiment has been varied in order to markedly change flow and fluid shear rate. Performance has been evaluated by how well the system maintains a physical uniformity throughout the vessel, whether mass transfer and the chemical reactions are occurring, and how much energy is required to meet design recoveries. During scale-up of the EIMCO bioreactors, care has been taken not to oversimplify the complexity associated with mixing phenomena.

CONCLUSION

Bioreactors serve a central role in biotechnological processes by providing the link between starting materials and final products. In most biological systems, there are complex series of reactions that must be optimized and coordinated in a very specific environment. Despite the complexity of biocatalytic processes, there is usually a rate-limiting step controlling the reaction, as well as a few secondary limitations. These limitations provide the basis for process design and bioprocess equipment specifications. The EIMCO Slurry Bioreactor has been designed to overcome these limitations encountered during the bio-oxidation of refractory gold ores and concentrates and hazardous waste bioremediation.

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