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Factors affecting bioleaching kinetics of sulfide ores using acidophilic micro-organisms

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Recovery of metal values from sulfide ores by use of acidophilic microorganisms is gaining importance. A number of commercial/pilot plants are setup to find out the techno-economic feasibility of the overall process. The main drawback in the process is the slow kinetics of dissolution of metal values from the sulfide ores. To make the technology more attractive the kinetics should be improved considerably. There are various factors which determine the overall kinetics such as bacterial activity and concentration, iron and sulfur oxidation, oxygen consumption, reactor design and nature of ore. A brief review has been made dealing with the above parameters.

Keywords: acidophilic, strain, oxidation, kinetics.

Introduction

The advancement of science has lead to the development of various new technologies that can meet the demand of ever-increasing population so that the mass at large would lead a comfortable life. Biotechnology is one of the recently developed frontier technologies and has been well exploited commercially, specially in the areas of pharmaceuticals, chemicals, food and enzyme production. The recovery of metal values from ores and minerals is also a part of vast area of biotechnology.

The popularity of biometallurgy is increasing due to two factors, mainly depletion of high grade ores and stricter enforcement of anti-pollution laws. The biometallurgy has several advantages compared to the conventional techniques, such as:

a) Ecofriendly process
b) Low capital investment
c) Low manpower and less requirement of costly sophisticated controls.

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Biometallurgy has a good potential for solving various metallurgical problems such as recovery of metal values from ores and minerals popularly known as bio-leaching, biodressing, biosorption and desulphurization of coal. Bioleaching technique has been widely used to recover metal values from ores. In this process the acidophilic microorganisms such as *Thiobacillus*, *Leptospirillium*, *Sulfobacillus*, *Acidianus* and *Sulfolobus* are generally used (Jordan *et al*. 1994, Bailey & Hansford 1993, Ahonen & Tuovinen 1994, Brierly 1993.) Recent trends also show that this technology can be applied to enhance the recovery of precious metals like gold and silver from refractory sulfide ores (Wang & Guan 1994, Miller & Hansford 1992, Jordan *et al.* 1996) as an alternative to pressure oxidation and roasting and a number of plants have been commissioned to recover gold in commercial scale (Hanzhao & Yongduo 1995, Dew *et al.* 1993). Apart from this, preliminary studies have also been carried out to recover metal values like zinc, cobalt, lead etc. from their respective sulfide ores (Donaldson *et al*. 1992, Holmes & Debus 1991).

Although the process is widely studied to recover the metal values from different ores but so far commercial application is only limited to low grade

ores. The primary reason for low commercial importance of this technique is the slow bioleaching kinetics. The present review discusses the important parameters determining the bioleaching kinetics.

Microorganisms

The acidophilic microorganisms that take part in dissolution of metals from the sulfide ores are autotrophic in nature. They can grow in inorganic medium having low pH values. They can tolerate high metal ion concentrations. The two main functions of this type of bacteria are oxidation of Fe(II) to Fe(III) and S to H_2SO_4.

These two reactions mainly control the reaction kinetics. To understand the reaction kinetics, it is mandatory to know about the characterization of the micro-organisms and conditions favorable to carry out the oxidation process.

The acidophilic microorganisms that actively take part in oxidizing Fe(II) to Fe(III) and S to H_2SO_4 are *Thiobacillus*, *Sulfolobus*, *Acidianus* and *Leptospirillium*. *Thiobacillus* species are rod-shaped, gram-negative, non-spore forming and mesophilic except the thermophilic *Thiobacilli*, which can grow at a higher temperature (Buchanan & Gibbons 1974). *Sulfobacillus* species are gram-positive, rod shaped with rounded or tapered ends and can grow at higher temperature. Acidianus species are spherical with tetrahedron, pyramid disc or saucer shaped lobes (Karavaiko 1988). *Leptospirillium* species are spiral shaped, non spore forming and gram negative (Blake *et al*. 1993).

Depending on their tolerance to temperature the acidophilic micro-organisms are categorized into three sub-groups such as mesophiles, moderate thermoacidophiles and extreme thermoacidophiles.

Mesophiles

Mesophiles are those micro-organisms which grow at a prevailing room temperature, i.e. 28–37°C. Among the mesophiles, the most popular and widely used strain is *Thiobacillus ferrooxidans* (Sugio & Akhter 1996, Kai *et al*. 1989, Das & Mishra 1996, Bhattacharya *et al*. 1990). Although many strains of *Thiobacillus ferrooxidans* have been isolated from different sources, most of the strains showed the following optimum growth conditions, i.e. pH 1.5–2.5 and a temperature range of 28–37°C (Ahonen & Tuovinen 1989). *T. ferrooxidans* being a lithotroph, derives energy for its growth by oxidizing Fe(II) to Fe(III) and sulfur, sulfide and different oxyanion of sulfur to sulfate. The assimilation of carbon dioxide by the microorganism is through Calvin Benson cycle catalysed by the ribulose-biphosphate carboxylase enzyme. The nitrogen requirement is met through ammonium compounds present in the medium. There is a poor resemblance of DNA homology between different strains of *Thiobacillus ferrooxidans*.

Leptospirillium ferrooxidans is an acidophilic microorganism like *Thiobacillus ferrooxidans*. The major drawback with *Leptospirillium ferrooxidans* is, it cannot oxidise sulphur to sulphate (Helle & Onken 1988). Therefore in order to oxidise Fe(II) and S it is essential to use a mixture of *Leptospirillium ferrooxidans* and *Thiobacillus ferrooxidans*.

Thiobacillus thiooxidans has the same morphological characteristics as that of *Thiobacillus ferrooxidans*. The main difference between the two microorganisms is that the former cannot oxidize Fe(II). The bacterium gets its energy by oxidizing S and soluble sulfur compounds to sulfate (Tuovinen *et al.* 1991, Suzuki *et al.* 1994).

Moderate thermophiles

Moderate thermophiles are able to grow at a temperature of around 50°C. There are a number of thermophilic strains isolated from different geothermal environments and mine sites (Tuovinen *et al.* 1991). An important moderate thermophile is *Sulfobacillus thermosulfidooxidans* which has the ability to oxidize sulfur and iron. (Lizama & Suzuki 1989, Morris & Barr 1985).

The bioleaching kinetics by moderate thermophiles is more than mesophiles as the leaching experiments are carried out at higher temperature. The moderate thermophiles are usually available inside the core of the dump as the core temperature is 10–15°C higher than the ambient.

Extreme thermophiles

The extreme thermophiles are those which can grow actively even at a temperature as high as 80°C. The most important extreme thermophiles belong to the genus *Sulfolobus* . A number of Sulfolobus species have been isolated such as *S. acidocaldarius*, *S. sofataricus*, *S.brierley, S. ambioalous*. They show the following properties such as :

(i) anaerobic growth coupled with reduction of elemental sulfur.
(ii) aerobic growth coupled with oxidation of sulfur.
(iii) optimum growth temperature of 65–70°C.
(iv) able to oxidize both Fe(II) to Fe(III) and sulfur to sulfate.

Since the extreme thermophiles can grow at higher temperature, so oxidation kinetics is more compared to mesophiles and moderate thermophiles (Lindstorm and Gunneriusson 1990).

The bioleaching kinetics in presence of extreme thermophiles is higher than that of mesophiles and moderate thermophiles. The bioleaching dissolution reaction is exothermic therefore the temperature increases during the reaction. So if extreme thermophiles are used then heat exchanger may not be required to control the leaching temperature.

Mechanisms of bacterial oxidation

As discussed above, the primary functions that are carried out by the micro-organism during bioleaching of sulfide ores are :

1. Oxidation of Fe(II) and S
2. Oxidation of metal sulfides to metal sulfates

Oxidation of Fe(II) and S

The oxidation of Fe(II) can be presented as:

$$Fe^{2+} + H^{+} + \tfrac{1}{2}\, O_2 \rightarrow Fe^{3+} + \tfrac{1}{2}\, H_2O$$

Cytochrome a and c along with the co-enzyme Q actively participates during Fe(II) oxidation (Sato *et al.* 1989). Co-enzyme Q acts as an intermediary electron carrier between Fe(II)-SO_4 organic complex associated with the cellular envelope (Nunzi & Bruschi 1993). Iron-cytochrome-c-oxidoreductase has been isolated, purified and characterized. The enzyme containing one atom of Fe(III) binds one atom of Fe(II), which reduces the enzyme bound iron and is then released. Then one molecule of oxidized cytochrome-c is bound by the enzyme, whose ferrous iron reduces the Fe(II) of the cytochrome-a. The iron of the enzyme is thus oxidized and the reduced cytochrome-c is released (Blake & Ginness 1993).

The iron oxidation by acidophilic microorganism is an important reaction in determining the dissolution kinetics. The Fe(III) reacts with metal sulfide(MS) to oxidize the same to MSO4 and the former reduces to Fe(II). The Fe(II) is again re-oxidized to Fe(III) which reacts with MS. Therefore the strain having higher Fe oxidation rate would favor MS dissolution rate. Elemental sulfur is present in the form of a circular 8-atom molecule. The sulfhydryl of the cell reacts with the sulfur to form an organic polysulfide. The sulfur oxidising enzyme then oxidise the terminal sulfur atom to SO_4 via intermediate SO_3 (Blake & Shute 1994). Sulfite thus formed is oxidised to sulfate by two principal methods such as via adenosine phosphosulfate or by cytochrome-c mediated oxidation (Silverman 1967, Srihari *et al.* 1992) .

The above conversion of SO_3^{2-} to SO_4^{2-} essentially follows 3-steps, such as, in the 1st step, APS is formed by the APS reductase followed by the action of ADP sulfurylase, the sulfate moiety of APS, is replaced by phosphoric acid to form ADP and SO_4^{2-} and in the final step, in the presence of adenylate kinase, the phosphoric acid group from one ADP molecule is transferred to another thus forming AMP and ATP. The iron and sulfur oxidation mecahnism is being reviewed by several authors (Kuenen *et al.* 1993, Wiertz 1993)

The bacterial S oxidation rate is vital in determining the MS dissolution rate in two ways, firstly the S produced during MS dissolution acts as a product layer and forms an impervious layer over the reactant thus retarding the reaction kinetics and secondly the in-situ production of H_2SO_4 which provides the necessary acidic environment required for the growth of acidophilic microorganisms.

Oxidation of metal sulfide(MS) to metal sulfate(MSO_4)

Conversion of metal sulfides to metal sulfates is possible either through indirect or direct mechanisms. In the indirect mechanism Fe(III) oxidised by the microorganism reacts with metal sulfide to form metal sulfate and in the process Fe(III) is reduced to Fe(II). The Fe(II) is further reoxidised to Fe(III) which again reacts with metal sulfide. But in the direct mechanism, the microorganism itself reacts with metal sulfide thus converting it to metal sulfate. In the direct mechanism initially a thin film is formed (Levia & Tributsch 1988) between the outer membrane of the attached bacterial cell and the surface of the sulfate mineral, followed by corrosion within the interfacial film. The mechanism of bacterial adhesion may be due to electrostatic, hydrophobic or other short or long range forces. The acidophilic microorganisms like *Thiobacillus* oxidise Fe(II) to Fe(III) in liquid medium, in which these are grown in absence of solid substrates. But if the bacteria are forced to utilize the mineral substrates to derive energy for their metabolism then it becomes necessary for the bacteria to secrete surface active reagents for the development of pilli that helps the same for attachment to the mineral surface (Natarajan 1995). It was reported that the development of flagella in *Thiobacillus ferrooxidans* depends on the culture conditions (Ohmura *et al.* 1996, Seeger & Jerez 1993).

So the necessary condition for direct mechanism is the attachment of bacteria with the sulfide minerals (Pogliani *et al.* 1990, Boon 1996). Espijo and Ruiz in 1987 attempted to determine the concentration of attached cell by radio-tracer technique . Several authors reported (Ohmura *et al.* 1994) that most of the cells are attached to the sulfide matrix. Yunker and Radovich in 1885 and 1986, concluded that the pyrite oxidation rate was dependent on the adsorption of *Thiobacillus ferrooxidans* to the pyrite surface. Konishi and Asai in 1993, postulated a direct bacterial action at mineral surfaces by means of a langmuir adsorption isotherm.

There are certain controversies regarding the direct mechanism, as the observation of pits (Normal & Snijman 1987, Zuo-Mei *et al.* 1984) does not conclusively prove the dissolution of metal sulfides through bacterial oxidation considering several other factors, such as, biooxidation mechanism, cyclic voltammetry analysis, amount of biomass attached on the mineral surface and bacterial kinetics using selective inhibitors (Chia *et al.* 1989; Hazen *et al.* 1986; Hazen *et al.* 1987; Boogerd *et al.* 1991; Verbaran & Huberts 1988; Boon 1996).

Factors affecting the bioleaching kinetics

There are various factors by which the oxidation reactions of acidophilic microorganisms are affected, such as :

1. Activity of microorganisms
2. Bacterial concentration
3. pH and Fe(III) concentration
4. Supply of oxygen
5. Product layer
6. Galvanic interaction

Activity of microorganisms

The activities of *Thiobacillus* and other acidophiles are indirectly measured in terms of iron and sulfur oxidation rate. The Fe and S oxidation rate differs from strain to strain (Mason *et al.* 1987, Bhattacharya *et al.* 1992). The difference in oxidation rate is due to many factors, such as change of morphology (Silverman and Roghoff 1961), difference in the chemical composition of lipopolysaccharide which is the main component of the cell-envelope (Vestal *et al.* 1973, Hirt & Vestal 1975), nutrient metabolism (Ralph 1985), tolerance towards organic materials (Wichlacz 1986) and DNA base ratio (Rawlings *et al.* 1986). High strain microbes can be isolated from different mine sources or by UV irradiation or genetic manipulation, the activities can be increased manifold. (Summers *et al.* 1986, Torma 1988). The adaptation technique is another way of increasing the bacterial activity (Babij & Madgwick 1983). Most of the metal ions are toxic to the micro-organisms, therefore the adaptation technique helps the micro-organism to survive and grow in alien conditions. *Thiobacilli* and other acidophilic micro-organisms have the capability to grow in the presence of various kinds of metal ions after adaptation. The adaptation also helps to reduce the lag period, thus enhancing the overall leaching kinetics (Attia 1993).

Bacterial concentration

Bacterial concentration in the solution is one of the controlling factors in determining the oxidation kinetics for sulfide minerals both in direct as well as indirect mechanism. In a continuous stirred tank reactor, the maximum concentration of microbial population varied between 10^3 to 10^9 cells/ml (Karavaiko 1988). Hence to increase the kinetics, the biopopulation has to be increased. The bacterial concentration in the lixiviant can be increased by harvesting the biomass from the bacterial solution and then inoculating the same in lesser volume of the solution. The harvesting can be done either by centrifugation or membrane filtration, but both the processes are rather costly and moreover it requires complicated instrumentation. The other way of increasing the microbial population is by the use of a biofilm type of reactor known as bacterial film oxidation (BACFOX) (Murayama *et al.* 1987, Gzrishin & Tuovinen 1988, Nikolov *et al.* 1988, Grishin *et al.* 1991). *Thiobacillus* and other acidophilic micro-organisms have special affinity towards jarosite, i.e. the microbial population gets concentrated on jarosite. Therefore, in a reactor if a thin film of jarosite can be developed under suitable conditions, then the acidophilic microorganisms would get necessary site for surplus growth. Pesic *et al.* in 1993, proposed a mechanism for jarosite formation and growth of microbial population over the same (Pesic & Kim 1993). The surface area of the reactor for jarosite precipitation can be increased by many ways such as by packing the reactor with corrugated sheet, tubes sulfide ores etc. The enhanced oxygen requirement by the bacterium can be supplied by aeration, either through biological contactor or distributor. Iron oxidation rate by the acidophilic microorganisms in this type of reactor

was reported (Murayama *et al*. 1987, Grishin & Tuovinen 1988, Nikolov *et al*. 1988, Grishin *et al*. 1991) to be high. The iron oxidation rate can reach a figure as high as 5–6 g/l.h. depending on the reactor design and the air utilization efficiency (Grishin *et al*. 1991). Apart from higher oxidation rate the other advantages of using this type of reactor are:

a. precipitation of excess iron compounds so that the quantum of precipitate during leaching can be minimized.
b. the reactor can also be utilized as an iron precipitator during further processing of leach liquor to recover the metal values (Toro *et al*. 1986, Kar *et al*. 1991).

The other alternative to increase the bacterial population in a solution is to apply an electrical potential. The bacterial population directly depends on the amount of Fe(II) oxidized. In a rough estimate, to produce 1g of biomass it requires to oxidize 100 g of Fe(II). Therefore to produce 1 g of biomass a very high amount of $FeSO_4$ is required. To reduce the $FeSO_4$ requirement the bacterial oxidation reaction can be carried out under applied potential. In this system, anode and cathode chambers are separated by a membrane which allows the mobility of the electron. In the cathode chamber the Fe(II) which is oxidised by bacteria is then reduced back to Fe(II) by application of potential. Therefore in the cathode cell there would be perennial source of Fe(II) without external addition. In an ideal condition if the bacterial iron oxidation rate is equal to iron reduction rate by applied potential then it would give a lixiviant containing high bacterial concentration as well as high oxidation potential which are both favorable for sulfide dissolution kinetics (Natarajan 1992).

pH and Fe(III) concentration

pH of the growth medium significantly affects the growth and activity of acidophilic microorganisms. Amaro *et al* in 1991 reported that *Thiobacillus ferrooxidans* responds to external pH changes by regulating the synthesis of several of its cellular components. According to Apel and Dugan in 1978, *Thiobacillus ferrooxidans* takes up H^+ from its external environment during the oxidation of Fe(II) to Fe(III). Hence H^+ is considered to be an essential nutrient for the bacterium. In general, the acidophilic bacteria, *Thiobacillus ferrooxidans,* are unable to initiate growth on Fe(II) at a pH greater than 3.0. The growth of the bacteria is usually initiated at a very low pH range and as the growth continues the pH of the medium also increases without affecting the bacterial activity (Apel & Dugan 1978). Several authors have reported that the bacterial activity is enhanced many folds by adaptation of the bacterial strain to the growth medium maintained at a suitable pH (Elzeky & Altia 1995, Menon & Dave 1995, Barr & Jordan 1992).

A low Fe(III) concentration enhances the oxygen uptake by the acidophilic microorganism. At a higher concentration, Fe(III) competitively inhibited ferrous iron oxidation by *Thiobacillus ferrooxidans* (Nyavor *et al*. 1996). Curtchet *et al.* 1992 reported that in the absence of other sources of energy the presence of soluble Fe(III) inhibits the growth of *Thiobacillus ferrooxidans.*

Supply of oxygen

Bacteria need oxygen during oxidation of Fe(II) and sulfur. The solubility of oxygen in water at 35°C is 8 g/m^3 and it decreases with increase of ionic concentration in the solution (Karavaiko 1988). As per the stochiometry, iron oxidation reaction by the bacterium requires 0.07 g of oxygen per gram of Fe(II) oxidized and this amount cannot be available from the solution considering the oxygen solubility, therefore, the extra oxygen has to be provided externally. The acidophilic micro-organisms are obligate aerobes and hence, low concentration of oxygen would impose constraints on the rate of oxidation by the same. It was reported by Liu *et al.* in 1987, that more than 0.2 g/dm^3 dissolved oxygen concentration in the solution is sufficient for the bacterium to retain the metabolic activities.

The copper solubilization rate in a dump or heap leaching operation greatly depends on the availability of oxygen. In an ideal situation the dump is constructed in such a way so that the air flow through the face of the dump and convects horizontally before the same ascends vertically. The main driving force of air inside the dump is the difference of air density. The differences of air density is directly related to the temperature distribution inside the dump. Due to the exothermic nature of sulfide dissolution, a temperature gradient is observed inside the dump. The air convection also depends on dump height, irrigation rate and dump permeability. Usually the air convection is good if the dump height is between 15–30 m and beyond this the air convection would be centered in and around the face. In a larger dump the higher solution flow rate favors a good air distribution inside the dump as the core temperature of the dump is higher and higher flow rate would bring down the

temperature where as a smaller dump requires a lower solution flow rate to attain good air convection. Apart from natural air convection, the availability of oxygen in a dump leaching operation can be increased by forced aeration. The oxygen deficiency in the dump usually occurs due to compaction of the ore and under these circumstances, the leaching rate can be improved by injecting air either through bore holes or tunnels (Hiskey & Bhapu 1987). A number of mathematical models have been developed regarding the air distribution inside the dump considering various leaching parameters such as temperature, permeability, flow rate, ore minerals (Pantelis & Ritchie 1991, 1992).

Bacterial leaching of sulfide ores has previously been limited to only dump or heap leaching operation, but due to possible utilization of acidophilic microorganism to treat the refractory ore containing precious metals in commercial scale, much interest is given to carry out the bioleaching studies in stirred reactors (Gormely 1992). In a stirred tank, the reactor design determines the overall oxygen mass transfer. The biological dissolution of sulfide ore is specific to the particular mineral/bacterial system. Therefore after evaluating the overall kinetics in terms of metal dissolution, iron as well as sulfur oxidation, the total demand of oxygen in the system can be evaluated. In order to utilize the oxygen to the maximum extent there should be proper design of the reactor, impeller, oxygen distribution as well as bubble size (Gormely 1990, Oolman *et al.* 1990, Boogerd *et al.* 1990, Fraser 1993, Hoffman *et al.* 1993). There are a number of proprietary technologies such as BIOX, Bac Tech and MINBAC process to treat the ore in a stirred reactor (Nicholsol *et al.* 1994, Brierley & Brans 1994, Torma 1991).

Product layer

The dissolution of sulfide ore through direct as well as indirect mechanism can be explained through shrinking core model (Sohn & Wadsworth 1979). In the shrinking core model, it is assumed that the substrate volume goes on decreasing with leaching. In this mechanism the following steps are involved:

a. The attacking species have to diffuse through the thin liquid film as well as the product layer to reach the substrate or reacting species.
b. The metal ions from the substrate have to diffuse from the product layer as well as the thin liquid film.
c. If the product layer is impervious then there would be gradual reduction of fluxes of the reactants and products and as the quantum of product layer increases the reaction rate falls off. On the contrary, if the product layer is porous or creates no additional diffusion barrier, then the reaction rate is independent of the product layer thickness. Therefore in shrinking core model, the product layer plays an important role in determining the rate kinetics.

In bioleaching process, there are three main product layers such as gypsum, precipitated iron compounds and sulfur. The ore contains various acid consuming gangue minerals such as carbonates and silicates and during leaching, the gangue minerals are neutralized by the acid forming gypsum. For better bacterial activity a part of the acid consuming minerals have to be neutralized as the acidophilic microorganism can grow in acidic medium. The iron chemistry is rather complicated and iron can be precipitated as hydroxide, goethite, jarosite or hematite. The formation of precipitated iron compounds depends on pH, Eh and concentration of Fe(III). Therefore, by carrying out the leaching experiment under control conditions, the extent of precipitation can be minimized (Canterford *et al.* 1985). Sulfur is formed during the dissolution of metal sulfides and forms a dense, tenacious, protective and insulating layer over the sulfide matrix. The layer limits the transport of species to and from the reaction site thereby limiting the dissolution rate of sulfide minerals. There are a number of reports (Ballester *et al.* 1992, Sukla *et al.* 1990, Ahonen & Tuovinen 1990) where the nature of product layer is changed from impervious to pervious layer by using catalyst like Ag ion and therefore the same would not hamper the reaction kinetics. The Ag ion reacts with the MS forming MSO_4 and Ag_2S. The Ag_2S then reacts with $Fe_2(SO_4)_3$ to form Ag ion and the cycle continues. The electrochemical reaction of Ag^+/Ag changes the nature of sulfur product layer from impervious to porous layer. Before using the Ag ion, the acidophilic microorganisms should be adapted to grow in presence of Ag as the same is extremely toxic (Tuovinen *et al.* 1985).

Galvanic interaction

The biokinetics of pyritic dissolution is faster compared to either sphalerite, galena or chalcopyrite. But when pyrite is in intimate contact with any of the above sulfide mineral then the rate of dissolution is just reversed, i.e. kinetics of dissolution of pyrite is least. The retardation of kinetics is due to galvanic interaction. The sulfide minerals are regarded as semiconductors and therefore can act as a carrier for electrons. Due to the electronic nature

of the sulfide minerals, the sulfide dissolution reaction can be considered as two half cells such as cathodic and anodic. Each sulfide mineral has its own rest potential depending on various factors such as crystallographic structure, solution composition, ionic concentration and nature of micro-organism (Natarajan 1992, Palencia *et al*. 1991). If pyrite is in intimate contact with sphalerite then pyrite having higher rest potential will act as a cathode and sphalerite as anode. Therefore sphalerite would be anodically dissolved whereas pyrite would be cathodically protected. Therefore in galvanic interaction the dissolution reaction of those sulfide minerals which acts as a cathode would be enhanced whereas the dissolution of anodic sulfide minerals would be minimized. So the galvanic interactions not only increase the dissolution reaction but preferentially leach a particular mineral. The galvanic effect depends on several factors (Natarajan 1988, Rao & Finch 1988, Jyothi *et al*. 1989) such as:

a. rest potential of sulfide minerals
b. nature and duration of contact
c. presence of oxygen
d. nature of electrolyte such as pH, conductivity and presence of other redox species.

Conclusion

Bioleaching process is a widely accepted commercial technology to recover metal values from low/off grade sulfide ores which cannot be exploited commercially by usual techniques. So far the application of bioleaching technique to recover metal values from high grade ore concentrate has very limited application due to slow kinetics. With the possible use of this technique to enhance the recovery of precious metals from refractory ores, much emphasis is now being given to modifying the kinetics. In-depth knowledge regarding the reaction mechanisms including the characterization of microorganism and the enzyme system is required in order to enhance the kinetics by finding out the rate determining steps.

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