



ISSN: 2319-5967

ISO 9001:2008 Certified

International Journal of Engineering Science and Innovative Technology (IJESIT)

Volume 3, Issue 4, July 2014

New non-toxic and secure technology for gold leaching by organic base polythionates

Vainshtein, M.^{1,2}, Smolyaninov, V.^{3*}, Shekhvatova, G.³

¹Institute of Biochemistry and Physiology of Microorganisms RAS, Pushchino, Russia; ²Pushchino State Institute of Natural Sciences, Pushchino, Russia; ³Scientific-industrial firm "Gamma", Pushchino, Russia

Abstract — *The review presents own experimental data and related publications related with the gold leaching. The well-known common process of the leaching with cyanide is dangerous, needs great water consumption, and expenses for remediation of the poisoned environment. The bioleaching accompanied with application of sulfuric acid is less effective and needs remediation of the acidified environment as well. In contrast, the gold leaching with thiosulfate and organic salts of polythionic acids (organic base polythionates) is not poisoning and does not need the following remediation of the sites. The method of these polythionates production is based on the Smolyaninov reaction, the paper presents it in stages and in details. The organic base polythionates are perspective for the prosperous gold leaching; their possible application in the gold leaching is compared with the gold leaching by cyanation.*

Index Terms — Bioleaching, Cyanide leaching, Gold leaching, Organic base polythionates, Polythionates, Smolyaninov reaction, Thiosulfate leaching.

I. INTRODUCTION

Gold leaching is the key process of gold mining. There are a few well-reputed leaching methods which use a number of different reagents. Recently, the most popular industrial processes included the leaching methods based on application of cyanide, thiourea, and thiosulfate. The cyanide leaching is the oldest and the leading one [1, 2], meanwhile, this reagent is highly toxic and its use leads to chronic poisoning of the soil in the areas of gold mining, causing severe ecological problems. Accordingly, its application suggests the following expenses for the following remediation of the sites.

In comparison to the cyanide leaching, the thiourea leaching is less toxic and more cost-effective, but it is still far from satisfactory too.

Leaching with thiosulfate is more advantageous technology [3, 4] because it is less expensive. The low cost of this reagent makes the thiosulfate leaching more attractive from an economical point of view. It is more eco-friendly too because the site contamination is not critical. The difficulty limiting application of the thiosulfate ($S_2O_3^{2-}$) or polythionates ($S_xO_6^{2-}$) leaching lies in their industrial production. The polythionates production based on use of well-known reactions of with halogens may lead i) to increase of their cost and ii) to degradation of equipment due to residual amounts of the halogens.

Till present time, the polythionates leaching is not common. There were a few reasons which limited application of the process. It has been considered for a long time that the compounds of the composition $H_2S_xO_6$ are rather unstable in aqueous solutions (under the form of some salts too). For many years it has been considered that the compounds with $x = 3-6$ known as polythionic acids are limited by the first four compounds. Polythionates have been neglected for many years due to their instability and to the formation of complex mixtures. Analysis of individual polythionate in solution was a complicated task. Nevertheless, we suggest that polythionates can find practical application both in general chemistry and in industry.

On the basis of experimental data, we discovered reactions of thiosulfuric acid accompanied with oxidation by mono- and polyatomic sulfur in the presence of "onium"-containing (i.e. ammonium-, sulfonium-, phosphonium-containing) compounds. Thus, it became possible to examine the problem of polythionic acid formation during thiosulfuric acid decomposition (Volynskiy-Smolyaninov reaction) [5]. As well, we succeeded to establish



ISSN: 2319-5967

ISO 9001:2008 Certified

International Journal of Engineering Science and Innovative Technology (IJESIT)

Volume 3, Issue 4, July 2014

experimentally that the interaction of SO₂ and of H₂S in ethanol in the presence of organic bases results in the formation of polythionic acids (here and below – Smolyaninov reaction) [6].

Unfortunately, the chemical reactions, where structure of the organic base determines the structure of the inorganic acid, are remaining unnoticed in spite of the possibilities they offer to obtain new chemical compounds with very interesting and earlier unknown properties. The present review discusses their possible production and application for innovative hydrometallurgical processes and, as well, as reagents for other new approaches (standards for analyses of sulfurous springs, industrial and domestic effluents, etc.).

II. BACTERIAL LEACHING FOR METAL RECOVERY

The first patents on gold recovery with leaching methods were claimed in 1887 in UK and in 1889 in USA [7]. Rate of the leaching is determined with composition of the raw mineral material, solution composition, temperature, pH, and redox potential (aeration). Application of microbial strains can catalyze some chemical reactions of the leaching. The most known examples of bioleaching are bacterial oxidation of insoluble metal sulfides with production of sulfuric acid on spot. Different microbial species can produce also other sulfur compounds (polythionates, etc) [8]. Low concentration of metal sulfides in ores makes no problem for bacteria which ignore surrounding mineral dumps. Most number of modern bioleaching technologies is oriented to application of super-acidophilic bacteria; ones as *Acidithiobacillus ferrooxidans* and *A. thiooxidans* which produce sulfuric acid and can live at pH lower than 1.0!

There is a wide taxonomic diversity of industrial microbial strains which belong to imperia: Bacteria and Archaea. For example, representatives of the following genera (i. e. formal groups identified by their genetic and metabolic features) are able of oxidizing of sulfides for the metal recovery: *Acidothiobacillus*, *Halothiobacillus*, *Thiobacillus*, *Leptospirillum*, *Acidiphilium*, *Sulfobacillus*, *Ferropasma*, *Sulfolobus*, *Metallosphaera*, and *Acidianus*. Thus, there are two main ways for development of the bioleaching biotechnologies: i) improving of the process organization (optimization of aeration, temperature, pre-treatment of the raw material, etc.) and ii) screening and selection of new strains with more high activity, more expand field of pH, more simple in culturing, etc.).

Typical approach is the same for bioleaching in whole, despite of metals and not only for sulfide ores which were mentioned as an example. But technological conditions vary for different types of ores and for different kinds of strains. For example, usual one-step process of bioleaching suggests temperature not higher than 40–45°C [9], otherwise mesophilic bacteria will die. In contrast, thermophilic and super-thermophilic bacteria shall need high temperature (for example: 70°C for *Sulfolobus* spp. [10, 11]). Application of super-acidophilic bacteria suggests that pH of the treated pulp is not higher than 2. From other hand, there are bacteria which could oxidize the metal sulfides of the ores under more neural or alkaline conditions [12, 13]. In whole, we can conclude that every type of mineral material and every type of the applied technological conditions are suited for some selected strains.

Innovations in the bioleaching can be determined as development of technologies in four fields, namely: i) material pre-treatment, ii) optimization of the technological conditions, iii) addition of supplements to activate aborigenic or/and supplied microorganisms, and iv) selection of new industrial strains. Some recent patents joint different applications together, for example: supplementation with salt for chemical treatment and with carbon substrate for microbial growth [14]. Some methodical applications are of great significance both for chemical and biological leaching. Increase of temperature affect rate of chemical reactions. It affects biochemical reactions of industrial strains too, however, bioleaching at high temperature suggests application of thermophilic bacteria (i. e. growing better at temperature above 45–50°C) or, at least, thermo tolerant ones (resistant to high temperature). Some patents do not mention Latin names of the strains but identify a temperature interval [15, 16].

Other affecting agents to regulate both chemical and biochemical reactions of leaching are pH and Eh (redox potential) of the medium. Usually they are regulated by addition of mineral acids and aeration. Each type of raw mineral material and each kind of industrial microbial strains need optimization of pH and Eh.



ISSN: 2319-5967

ISO 9001:2008 Certified

International Journal of Engineering Science and Innovative Technology (IJESIT)

Volume 3, Issue 4, July 2014

Development of the leaching methodology and technology is cheaper when it applies not new chemical supplements or increase temperature and aeration by the energy expenses but new industrial strains. Search, screening and selection of new strains are basement of the progressive biogeotechnology. The first industrial bacterial strains for leaching belonged traditionally to the classic thionic group («thiobacilli»). All patents of 90-s include these species: *Thiobacillus* (in present renamed into *Acidithiobacillus thiooxidans*, *T. (A.) ferrooxidans*, and *Leptospirillum ferrooxidans* [17, 18]. However, since beginning of the current century, the list of industrial species expanded and a patent includes representatives of different genera: *T. ferrooxidans*, *T. thiooxidans*, *L. ferrooxidans*, *T. caldus*, *Acidimicrobium sp.*, and *Sulfolobus sp.* [19]. Appearance of the last ones in the patent text is affiliated with their ability to oxidize sulphur compounds at high temperature. Data on activity of the leaching industrial strains at different temperatures is a common object of discussion in research articles which are published during preparing patents [20]. Recently a special attention was paid to the archaeal genus *Sulfolobus* including *S. metallicus* that grows at 70°C and is resistant against toxicity of dissolved heavy metals and floating agents [21, 22]. Toxicity of the leached heavy metals is not a limiting factor because bacteria can be adopted [23] or modified with specific plasmid of resistance [24].

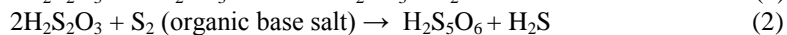
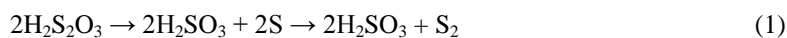
Microbiological methods permit also to increase recovery of metals via the mutants formation, the example is a transformation of the leaching industrial thermophilic strain *Acidianus brierleyi* (formerly *Sulfolobus*) [25]. In whole, we can conclude that bioleaching is a rapidly evolving field of the hydrometallurgy.

There is a broad field for development of bioleaching. However, to create a new biotechnology that shall be both profitable and more eco-friendly, it is necessary, at least, to minimize input of sulfuric acid as an industrial supplement. It seems that the same effects of bioleaching can be reached with a minimum of the technical acid via application of moderate acidophilic bacteria [26]. The suggested replacement of strong acidophilic bacteria for moderate acidophilic ones shall decrease addition of sulfuric acid, shall decrease prime cost of nickel, and, as well, shall decrease expenses for the site remediation, however, it will slow the metal recovery.

III. FORMATION OF ORGANIC BASE POLYTHIONATES

Formation of pentathionates in the reaction of acids with thiosulfate in the presence of some organic bases

We observed that acidifying thiosulfate solutions in the presence of some higher amine salts or ammonium base salts resulted in their precipitation as oily substance and the reaction mixture smelled as hydrogen sulfide [27]. The pentathionic acid is formed, after acidifying some thiosulfate in the presence of salts of some amines and quaternary ammonia, according to the following Equations (1-3):



Hydrogen sulfide emitted under the reaction (2) immediately reacted with the sulfurous gas that had been formed at the thiosulfuric acid decomposition. At this moment, sulfur is emitted again and the whole process repeats from the beginning until complete transformation of thiosulfuric acid to pentathionic acid (3). The reaction (2) was not described in literature before our publication.

Formation of tetra- and pentathionates in reaction of acids with thiosulfates in the presence of organic base salts

During our study of the thiosulfuric acid transformations in the presence of organic bases, we synthesized N-alkyl pyridinium, N-alkyl quinolinium, and dimethylalkylphenylammonium chlorides containing from 5 to 10 carbon atoms in the alkyl chain [28]. We studied the dependency between the polythionic acid formation and the structure of nitrogen bases in more details, and our investigations showed that in the presence of salts of dimethyldecyl-, dimethylnonyl- or dimethyloctylphenylammonium the thiosulfuric acid is transformed to pentathionic acid according to the Equation (3).



ISSN: 2319-5967

ISO 9001:2008 Certified

International Journal of Engineering Science and Innovative Technology (IJESIT)

Volume 3, Issue 4, July 2014

Under the effect of N-alkylpyridinium and N-alkylquinolinium ions, the thiosulfuric acid forms pentathionic and tetrathionic acids, the last being formed as the main compound in many cases.

At room temperature, the transformation of thiosulfuric acid to tetrathionic or pentathionic acid occurs with rather high yields in the presence of organic base ions, containing an alkyl chain with at least 7-6 carbon atoms. Further reduction of the alkyl chain length leads to a drastic decrease in tetrathionate (and pentathionate) yields and to a respective increase in sulfur yields according to the reaction (1).

Under the effect of a catalyst, namely—an organic base ion, the monatomic sulfur formed during the partial decomposition of the thiosulfuric acid according to the Equation (4) acquires more expressed oxidizing properties, which makes it possible to start a reaction (5) not described in literature. It is easy to understand that the reaction (5) is similar to the reaction of oxidizing thiosulfuric acid with iodine. The hydrogen sulfide emitted reacts with H_2SO_3 , and sulfur formed in this case reacts again according to the Equation (5). The process is described by the Equation (6):



It is of interest to clarify the specificity degree of the effect of ammonium ions and if it represents a specific case of a common phenomenon consisting in the effect of the onium ions on the oxidizing capacity of monatomic and diatomic sulfur. We found out that sulfonium and phosphonium ions manifested some activity in the process under study, similar to the ammonium ions activity.

Formation of organic base polythionates

The research we carried out about the effect of the organic base structure on the preferred formation of tetra- or pentathionic acid with acidifying the aqueous solution of sodium thiosulfate and the organic base salt enables us to arrive at some general conclusions [29]:

1. Primary amines do not favor the formation of polythionic acids.
2. Secondary amines do not favor the formation of polythionic acids, but in the presence of at least one hydro carbonic radical with rather long chains it is possible to get tetrathionic acid. In the presence of a secondary butyloctadecylamine, we registered the formation of tetrathionic acid.
3. Tertiary amines having one hydro carbonic radical containing more than 5 carbon atoms favor the formation of tetrathionates, and tertiary amines with 2 or 3 hydro carbonic radicals of this type form pentathionates, their yields increasing with the increase of the hydro carbonic chain length.
4. Quaternary ammonium bases, in the presence of two rather long alkyl chains, favor the formation of pentathionates.
5. N-alkylquinolinium, starting from N-hexylquinolinium, favors the preferred formation of tetrathionic acid.
6. N-alkylpyridinium, starting from N-hexylpyridinium, forms a mixture of polythionates.
7. Dimethylalkylphenylammonium, starting from dimethylhexylphenylammonium, forms pentathionates.
8. N-methyl-8-alkoxyquinolinium and 8-alkoxyquinolinium with an alkyl radical containing 5 and more carbon atoms form tetrathionates.
9. Diisoamyl- β -alkoxyethylammonium ions and diisoamyl- β -alkoxyethylammonium ions form pentathionates.
10. Sulfonium ions, depending on the structure, form tetra- and pentathionates.

In all the cases, only neutral salts of polythionic acids were formed. So, a reaction of forming organic base polythionates with acidification of thiosulfate in the presence of organic base salts was discovered:



Where R_1 , R_2 , and R_3 are hydro carbonic radicals with carbon chains of C_1 to C_{18} , one of them being at least C_6 ,
N is sulfonium, phosphonium or heteroatomic nitrogen,

Hal is Cl^- , Br^- , J^- , NO_3^- or other anion,

n is number of sulfur atoms (from 3 to 6, mainly 4-5).



ISSN: 2319-5967

ISO 9001:2008 Certified

International Journal of Engineering Science and Innovative Technology (IJESIT)

Volume 3, Issue 4, July 2014

Despite the fact that this presentation is a review, this equation is given for the first time in scientific literature. This Volynskiy-Smolyaninov reaction was published only as a “Method of obtaining polythionates of higher amines and onium compounds” claimed with the USSR Author’s certificate (some kind of the former Soviet patent) [5].

To obtain the organic base polythionates, thiosulfuric acid or sulfurous acid is used in excess which leads to the formation of acid salts of these acids.

Oxidation of the forming salts of mono-, di-, triatomic and polyatomic sulfur leads to the formation of trithionates, tetrathionates, pentathionates, etc.

The presence of an organic base favors the increase in the oxidative capacity of sulfur, and the number of hydrocarbonic chains and their length determine the accessibility of the hydrogen from the acid for the oxidizer and the stability of the chain to be formed. Assuming that the alkyl radicals protect the sulfur chain against hydrolysis, one can understand why 2 or 3 long alkyl radicals in tertiary amines or in quaternary ammonium bases shift the reaction to the formation of longer polythionic acids, and in the presence of OH⁻ groups in alkyl chains, the polythionates are not formed, the lower amines neither favoring the formation of polythionates.

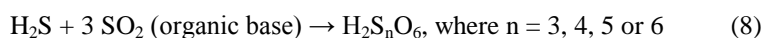
The length of a chain with 5 C-atoms is almost equal to the chain of 4 S-atoms, and this fact seems to determine the minimum alkyl chain lengths in bases, starting from which it becomes possible to form polythionic acids while acidifying thiosulfate in the presence of organic bases.

The excess of HSO₃⁻ or HS₂O₃⁻ ions and the structure of the organic base finally determine the preferred yield of such or another polythionic acid.

These experimental data showed for the first time that the length of the Sn chain in organic base polythionates depends on the length of radicals and their amount [30].

In general, approximately 140 new chemical compounds were synthesized when studying the reactions of the organic base polythionate formation with acidifying the thiosulfate and the organic base salt in water and those of the organic base polythionate formation at the interaction of an organic base with SO₂ and H₂S in alcohol.

Interaction of alcohol solutions of SO₂ and H₂S (in ethanol) led to quantitative formation of sulfur. When organic bases are present in the reaction mixture, then there are formed polythionates of these organic bases with a very high yield and some amount of sulfur as a result of the excess of SO₂ and H₂S. The preferred yield and relation of various polythionates depended on the structure of the organic base (7) [6].



This novel chemical reaction, the Smolyaninov reaction, was claimed as the Patent RU 2404948 “Method of obtaining organic base polythionates” [6].

IV. POLYTHIONATES IN THE GOLD LEACHING

It was proposed to use polythionate organic bases as efficient gold eluting agents from an anion exchanger, after leaching with a thiosulfate [31, 32]. Thiosulfate leaching of gold represents a potentially attractive alternative to a respective cyanation process at least for three types of auriferous ores. Firstly, in auriferous ores containing an organic carbon material, the recovery of gold by thiosulfate leaching is generally significantly higher due to the insensibility of the thiosulfate complex of gold to the preg-robbing or, in other words, to the re-sorption or solution depletion. In the second place, Au, Cu-containing ores often are not convenient for the cyanation process due to high cyanide consumption by copper in the ore, which leads to an unacceptably high cost. Thiosulfate does not easily react with copper minerals, and the lower reagent cost and the lower sulfate consumption compared to cyanides lead to a lower cost in such a situation. Finally, there are some layers of auriferous ore that cannot be treated by cyanation for being located in a delicate environment. The thiosulfate



ISSN: 2319-5967

ISO 9001:2008 Certified

International Journal of Engineering Science and Innovative Technology (IJESIT)

Volume 3, Issue 4, July 2014

leaching reduces the load onto environment since the chemical reagents used in this process are already used in agriculture.

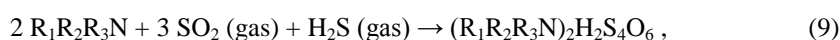
As shown in the literature [29], the gold-thiosulfate complex is eluted by polythionates that are produced with the use of iodine, bromine, and hydrogen peroxide as oxidants. Thus minor residual amounts of iodine and bromine lead to very severe corrosion of the process equipment. To avoid adverse effects, we proposed to apply organic base polythionates for eluting a gold-containing complex from a sorbing agent [6, 33].

Method of gold recovery from sulfide auriferous ores has already been proposed [33]. The invention relates to the method of gold recovery from powdered sulfide auriferous ores after their unlocking by bacterial leaching or by oxidation roasting, or by autoclave oxidation. Examples of bioleaching are bacterial oxidation of insoluble metal sulfides with production of sulfuric acid on spot. It is interesting that some leaching bacteria can produce also other sulfur compounds including the mentioned polythionates [34]. Low concentration of metal sulfides in ores makes no problem for bacteria which ignore surrounding mineral dumps. Most number of modern bioleaching technologies is oriented to application of super-acidophilic bacteria, which produce sulphuric acid and can live at pH lower than 1.0. Toxicity of the leached heavy metals is not a limiting factor because some bacterial strains can be adopted [23] or modified with the specific plasmid of resistance [24].

The proposed method of the gold recovery comprises leaching with a solution of a mixture of sodium and ammonium hydrosulfite and thiosulfate, by sorption of the thiosulfate-gold complex on a highly basic anion exchanger and by isolation of the highly basic anion exchanger, the sorption being carried out 2-10 hours after the leaching. Then the thiosulfate-gold complex is eluted with a solution of organic and inorganic base polythionates with concentration of 0.2 to 10%. Gold is isolated from the gold-containing eluate by a decomposition reaction or by an electrochemical method. In this case, the decomposition reaction is performed with such metals as magnesium, zinc or iron, or with sulfides. Then the highly basic anion exchanger is regenerated with a solution of a mixture of sodium and ammonium sulfite and sulfate. After the highly basic anion exchanger regeneration, it is transferred to the process of the thiosulfate-gold complex sorption. The technical advantage resides in a faster leaching, a higher gold yield and a lower consumption of the leaching agent.

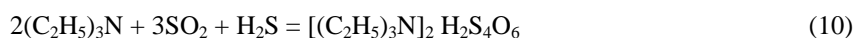
Method of obtaining organic base polythionates was not discussed in international scientific literature earlier but just claimed with a patent [6]. Meanwhile, the invention relates to a method of obtaining organic base polythionates used for biological hydrometallurgy processes [33]. It is impossible to obtain polythionates well soluble in water, by known processes, since for a successful process run, it is necessary for the organic base to have at least one aliphatic radical with the carbon atom number of at least 7. It is propose a method of obtaining organic base polythionates, in which the organic base solution in an organic solvent is treated with sulfurous gas and later by hydrogen sulfide. After separating precipitated sulfur and distilling off the organic solvent, the organic base polythionate is recovered. No limitations exist for the organic base structure in this reaction (9).

Summarizing the general formula of the Smolyaninov reaction, the reaction to form any organic bases [6], it can be presented as follows:



Where R_1 , R_2 , and R_3 are hydrocarbon radicals of C_1-C_{18} and N represents both ammonium and other onium bases.

In a particular case, while using triethylamines



Where the reaction gives a colorless oily liquid similar to glycerol.



ISSN: 2319-5967

ISO 9001:2008 Certified

International Journal of Engineering Science and Innovative Technology (IJESIT)

Volume 3, Issue 4, July 2014

Since the structure of the polythionic acid depends on the base structure, the number of sulfur atoms can be different, i.e. 3, 5, 6, etc. These equations are presented for the first time.

V. CONCLUSIONS

Gold leaching can be successfully realized with polythionates but their production till present was limited by complication. The paper describes different stages, conditions, and schemes of the polythionates production. In whole, a new innovative approach is shown suggesting that the use of polythionates (or of combined thiosulfate) leaching together with elution of gold complexes with organic bases polythionates makes the gold leaching process in mining more safe and thus more economical than cyanation. The process is based on the Smolyaninov reaction to produce polythionates that is presented in details. The bench-scale experimental data of the authors suggest some future scaling up of the process and the polythionates application in fields of the gold mining and the recovery of valuable metals from solid wastes.

ACKNOWLEDGMENT

The work was partially supported by the Russian Federal Program, Agreement 14.BBB.21.0146 “Developing effective bioleaching technology of valuable metals from solid waste”.

REFERENCES

- [1] T. I. Mudder and M. M. Botz “Cyanide and society: a critical review,” *Eur. J. Miner Process Environ. Prot.*, vol. 4, pp. 62–74, 2004.
- [2] G. Hilson and A. J. Monhemius “Alternatives to cyanide in the gold mining industry: what prospects for the future?,” *J. Clean Prod.*, vol. 14, nos. 12–13, pp. 1158–1167, 2006.
- [3] D. M. Muir and M. G. Aylmore “Thiosulfate as an alternative lixiviant to cyanide for gold ores,” *Dev. Miner Process*, vol. 15, pp. 541–560, 2005.
- [4] M. G. Aylmore “Alternative lixiviants to cyanide for leaching gold ores,” *Dev. Miner Process*, vol. 15, pp. 501–539, 2005.
- [5] V. V. Smolyaninov and N. P. Volynskiy “Method of producing polythionates of higher amines and onium bases,” (in Russian), USSR Author’s certificate 175956, *Bulletin of Inventions*, no. 21, 1965.
- [6] V. V. Smolyaninov, G. V. Shekhvatova and V. A. Smagin “Method of obtaining organic base polythionates,” (in Russian), *Bulletin of the Federal Institute of Industrial Property*, no. 33, RU Patent 2404948, 2010.
- [7] J. C. McArthur, R. W. Forrest, and W. Forrest “Process obtaining gold and silver from ores,” *Brit. Patent 14174*, 1887; *US Patent 403202*, 1889.
- [8] A. Schippers, P.-G. Jozsa, and W. Sand “Sulfur chemistry in bacterial leaching of pyrite,” *Appl. Environ. Microbiol.*, vol. 62, no. 9, pp. 3424–3431, 1996.
- [9] D. W. Dew, C. van Buuren, K. McEwan, and C. Bowker “Bioleaching of base metal sulphide concentrates: A comparison of mesophile and thermophile bacterial cultures,” *Process Metallurgy*, vol. 9, no. 1, pp. 229–238, 1999.
- [10] H. Jordan, A. Sanhueza, V. Gautier, B. Escobar, and T. Vargas “Electrochemical study of the catalytic influence of *Sulfolobus metallicus* in the bioleaching of chalcopyrite at 70°C,” *Hydrometallurgy*, vol. 83, nos. 1–4, pp. 55–62, 2006.
- [11] D. Mikkelsen, U. Kappler, R. I. Webb, R. Rasch, A. G. McEwan, and L. I. Sly “Visualization of pyrite leaching by selected thermophilic archaea: Nature of microorganism–ore interactions during bioleaching,” *Hydrometallurgy*, vol. 88, nos. 1–4, pp. 143–153, 2007.
- [12] M. Ostrowski and A. Sklodowska “Acid leaching in alkaline environment,” *Bulletin of the Polish Academy of Sciences, Biol. Sci.*, vol. 44, pp. 279–283, and 1996.
- [13] J. Xia, A. Penga, H. Hea, Y. Yanga, X. Liu, and G. Qiu “A new strain *Acidithiobacillus albertensis* BY-05 for bioleaching of metal sulfides ores,” *Transactions of Nonferrous Metals Society of China*, vol. 17, no. 1, pp. 168–175, 2007.
- [14] T.L. Young, M. G. Greene, D. R. Rice, K. L. Karlage, and S. P. Premeau “Methods for leaching of ores,” *US Patent Application 20030075021*, 2003.



ISSN: 2319-5967

ISO 9001:2008 Certified

International Journal of Engineering Science and Innovative Technology (IJESIT)

Volume 3, Issue 4, July 2014

- [15] P.A. Spencer, J. R. Budden, J. Barrett, M. N. Hughes, and R. K. Poole "Oxidation of metal sulfides using thermotolerant bacteria," US Patent 5429659, 1995.
- [16] W. J. Kohr, V. Shrader, and C. Johansson "High temperature heap bioleaching process," US Patent Application 20020194962, 2002.
- [17] R. P. Hackl, F. R. Wright, and A. Bruynesteyn "Chemical/biological process to oxidize multimetallic sulphide ores," US Patent 4987081, 1991.
- [18] R. P. Hackl, F. R. Wright, and A. Bruynesteyn "Bacteria for oxidizing multimetallic sulphide ores," US Patent 5089412, 1992.
- [19] D. W. Dew and D. M. Miller "Copper, nickel and cobalt recovery," US Patent 6245125, 2001.
- [20] D. W. Dew, C. van Buuren, K. McEwan, and C. Bowker "Bioleaching of base metal sulphide concentrates: A comparison of mesophile and thermophile bacterial cultures," *Process Metallurgy*, vol. 9, no. 1, pp. 229–238, 1999.
- [21] H. Jordan, A. Sanhueza, V. Gautier, B. Escobar, and T. Vargas "Electrochemical study of the catalytic influence of *Sulfolobus metallicus* in the bioleaching of chalcopyrite at 70 °C," *Hydrometallurgy*, vol. 83, nos. 1–2, pp. 55–62, 2006.
- [22] M. Dopson, J.-E. Sundkvist, and E. B. Lindström "Toxicity of metal extraction and flotation chemicals to *Sulfolobus metallicus* and chalcopyrite bioleaching," *Hydrometallurgy*, vol. 81, nos. 3–4, pp. 205–213, 2006.
- [23] C. Astudillo and F. Acevedo "Adaptation of *Sulfolobus metallicus* to high pulp densities in the biooxidation of a flotation gold concentrate," *Hydrometallurgy*, vol. 92, nos. 1–2, pp. 11–15, 2008.
- [24] A. Filonov, L. Akhmetov, A. Vatsurina, and M. Vainshtein "Isolation of plasmids of nickel resistance from indigenous thiobacteria inhabiting nickel ores," Presentation, The 3rd Congress of European Microbiologists (FEMS), Gothenburg, Sweden, 2009.
- [25] Ch. Meng, X. Shi, H. Lin, J. Chen, and Y. Guo "UV induced mutations in *Acidianus brierleyi* growing in a continuous stirred tank reactor generated a strain with improved bioleaching capabilities," *Enzyme and Microbial Technology*, vol. 40, no. 5, pp. 1136–1140, 2007.
- [26] M. Vainshtein "Bioleaching of metals as eco-friendly technology," In: "Current Environmental Issues and Challenges". pp. 197-205, G. Cao and R. Orrù (Eds.), Springer, 2014.
- [27] N. P. Volynskiy "Formation of pentathionates at the reaction of acids with thiosulfates in the presence of salts of some organic bases," (in Russian). *Zhurnal Obshchei Khimii (Journal of General Chemistry)*, vol. 29, no. 7, pp. 2115–2119, 1959.
- [28] N. P. Volynskiy and V. V. Smolyaninov "Formation of tetra- and pentathionates at the reaction of acids with thiosulfates in the presence of salts of some organic bases," (in Russian). *Zhurnal Obshchei Khimii (Journal of General Chemistry)*, vol. 33, no. 5, pp. 1456–1461, 1963.
- [29] V. V. Smolyaninov, G. V. Shekhvatova, and M. B. Vainshtein "Gold leaching by polythionates (new non-toxic technology)," (in Russian) *Proceedings of the 4th International Congress "Non-Ferrous Metals 2012"*, pp. 456–462, 2012.
- [30] V. V. Smolyaninov "Electrophoresis and thin-layer chromatography of organic base polythionates," *J. Chromatogr.*, vol. 53, pp. 337–343, 1970.
- [31] C. Fleming, J. Wells, and K. G. Thomas "Process for recovering gold from thiosulfate leach solutions and slurries with ion exchange resin," US Patent 6344068, 2002.
- [32] I. J. Matthew "Process for recovering metals from resins," International Patent Application WO2007137325, 2007.
- [33] V. V. Smolyaninov, G. V. Shekhvatova, and V. A. Smagin "Method for recovering gold from sulfide auriferous ores," *Bulletin of the Federal Institute of Industrial Property*, no. 10, RU Patent 2385959, 2010.
- [34] A. V. Vatsurina, T. Z. Esikova, V. P. Kholodenko, M. B. Vainshtein, and V. I. Dubkova "Corrosion of pipe steel samples and conjugated conversion of sulfur compounds by thionic bacteria *Halothiobacillus neapolitanus* DSM 15147," *Applied Biochemistry and Microbiology*, vol. 41, no. 5, pp. 495–498, 2005.