Hydrometallurgy 94 (2008) 2–7

Contents lists available at ScienceDirect

Hydrometallurgy

journal homepage: www.elsevier.com/locate/hydromet

A perspective on developments in biohydrometallurgy

James A. Brierley *

Brierley Consultancy, LLC, 2074 East Terrace Drive, Highlands Ranch, Colorado 80126-2692, USA

ARTICLE INFO

Available online 29 May 2008

Keywords:
Archaea
Acidianus
Bioleaching
Biooxidation pretreatment
Chalcopyrite
Covellite
Heap leaching
International Biohydrometallurgy Symposia
Metallospheara
Molybdenite
Refractory gold ore
Sulfobacillus
Thermophilic

ABSTRACT

My perceptions of the biohydrometallurgical field span four decades and stem from being a professional microbiologist conducting academic research and research for process development and applications of thermophilic microorganisms and heap bioleach processes. My experiences have given me an appreciation for knowledge gained through fundamental research and the transfer of this knowledge to development of commercial-scale applications of microbial processes. The symposia series for international activities in biohydrometallurgy have been a major factor in advancing knowledge and applications for microbial bioleach systems. The first international biohydrometallurgy meeting was held in Braunschweig, Germany in 1977. This was the predecessor for the International Biohydrometallurgy Symposia. As evident from the Symposia, advances in development and applications of biohydrometallurgy technologies follow an evolutionary, rather than revolutionary progression from demonstration of knowledge at the laboratory scale to engineering commercial plants.

1. Introduction

This paper presents a brief history of the International Biohydrometallurgy Symposia and my experiences with two biohydrometallurgy applications — use of archaea and bacterial thermophiles and the development of bioleach heap technology. The discovery of iron- and sulfur-oxidizing acidophilic archaea in 1965 was followed with research defining their role in oxidation of sulfide minerals and with commercial-scale application beginning in 2000. The archaea were found to be effective for biooxidation of pyrite and bioleaching the primary copper sulfide minerals, chalcopyrite, enargite and covellite. Bioleaching of chalcopyrite concentrate was developed and evaluated at commercial scale in 1995. Further work is in progress for use of the archaea to bioleach lower grade chalcopyrite ore in engineered heaps. The archaea are also capable of bioleaching molybdenum from highly refractory molybdenite. Bioleach heap processes have been refined from the initial application of copper leach dumps in the 1950s to engineered heaps for bioleaching secondary copper (chalcocite) ore and pretreatment of sulfidic-refractory gold ore. Commercial applications of minerals biooxidation demonstrate the complexity of the microbial populations involved in the processes. Biooxidation heap processes are now inoculated with the microbe populations most suited to the conditions anticipated to develop in a heap process. One example is addition of thermophilic iron-oxidizing bacteria and archaea to a heap which heats to temperatures exceeding the ability of mesophilic bioleach bacteria to survive.

2. International Biohydrometallurgy Symposia

The International Biohydrometallurgy Symposia (IBS) conference series are an integral part of the development of knowledge and practical technologies of biohydrometallurgy. The first meeting was held in 1977 in Wolfenbüttel, Germany. This meeting established the forum for presentations in fundamental research and applications of microbial processes for biohydrometallurgy. The meetings in Germany and Canberra, Australia in 1980 were organized in conjunction with the International Symposium for Environmental Biogeochemistry (ISEB). Thereafter the IBS became independent of ISEB. The IBS series evolved to occur every two years in different countries. Meetings continue to be based on volunteer organization with session topics designated by the host organizers. An important value of the IBS is provided through published conference proceedings making available a history of research and developments over four decades of accomplishments (Table 1). The IBS is continuing with the 2009 meeting to be held in Bariloche, Argentina, September 13–17 (www.ibs2009.org.ar). The 2011 IBS will be in China.

Documentation of advances in research and development of biohydrometallurgy has been provided through other publications in addition to the IBS conference proceedings. A comprehensive book on the topic was published by Rossi (1990). Other conferences and

* Fax: +1 303 683 1944.
E-mail address: j.brierley@worldnet.att.net.

0304-386X/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.hydromet.2008.05.014

Table 1
International Biohydrometallurgy Symposia

Year	Location	Title	Reference
1977	Wolfenbüttel, Germany	Conference Bacterial Leaching 1977	Schwartz (1977)
1977	Socorro, NM USA	Metallurgical Applications of Bacterial Leaching and Related Microbiological Phenomena	Murr et al. (1978)
1980	Canberra, Australia	Biogeochemistry of Ancient and Modern Environments	Trudinger et al. (1980)
1980	Pecs, Hungary	Use of Microorganisms in Hydrometallurgy	Anonymous (1980)
1983	Sardinia, Italy	Recent Progress in Biohydrometallurgy	Rossi and Torma (1993)
1986	Vancouver, Canada	Fundamental and Applied Biohydrometallurgy	Lawrence et al. (1986)
1988	Coventry, England	Biohydrometallurgy	Norris and Kelly (1988)
1989	Jackson Hole, WY USA	Biohydrometallurgy	Salley et al. (1989)
1991	Troia, Portugal	9th International Symposium Biohydrometallurgy	(abstracts only)
1993	Jackson Hole, WY USA	Biohydrometallurgical Technologies	Torma et al. (1993a,b)
1995	Vina del Mar, Chile	Biohydrometallurgical Processing	Vargas et al., (1995) and Jerez et al., (1995)
1997	Sydney, Australia	Biotechnology Comes of Age	Australian Mineral Foundation (1997)
1999	Madrid Spain	Biohydrometallurgy and the Environment Toward the Mining of the 21st Century	Amils and Ballester (1999)
2001	Minas Gerais, Brazil	Biohydrometallurgy: Fundamentals, Technology and Sustainable Development	Ciminelli and Garcia (2001)
2003	Athens, Greece	Biohydrometallurgy "A Sustainable Technology in Evolution"	Tsezos et al. (2004)
2005	Cape Town, South Africa	16th International Biohydrometallurgy Symposium	Harrison et al. (2005)
2007	Frankfurt, Germany	Biohydrometallurgy: From the Single Cell to the Environment	Schippers et al. (2007)

meetings have also resulted in published proceedings documenting historical developments in the field (Ehrlich and Holmes, 1986; Australian Mineral Foundation, 1993, 1994, 1999). Recent edited books cover a number of specific topics in biohydrometallurgy (Donati and Sand, 2007; Rawlings, 1997; Rawlings and Johnson, 2007).

3. Thermophilic microbes in biohydrometallurgy

Since the inception of the International Biohydrometallurgy Symposia series there have been significant advancements in understanding the extent and diversity of microbes in biohydrometallurgical processing. Early development efforts focused on what were then called *Thiobacillus ferrooxidans* and *Thiobacillus thiooxidans* now both in the genus *Acidithiobacillus*. Today we know there are many different genera and species of microbes capable of sulfur and iron oxidation processes for transforming minerals. Among these are the thermophilic archaea and bacteria.

3.1. Thermophilic iron-oxidizing archaea

One of the first acidophilic, sulfur-oxidizing archaea was isolated from an acidic thermal spring in Yellowstone National Park, Wyoming, USA in 1965 (Brierley, 1966). This microbe was characterized and found capable of utilizing ferrous iron as an energy source (Brierley and Brierley, 1973). The archaean was subsequently named *Acidianus brierleyi* (Segerer et al., 1986). The ability of *A. brierleyi* to oxidize iron was a strong indication of its potential for application in biohydrometallurgical processing.

The archaean demonstrated a remarkable characteristic for bioleaching the very refractory primary copper sulfide mineral chalcopyrite; this was first reported in 1978 (Brierley and Brierley, 1978). Attempts to bioleach chalcopyrite with mesophilic bacteria such as *A. ferrooxidans* were not successful. Comparison of mesophilic bioleaching with thermophilic bioleaching of chalcopyrite (Table 2) illustrated the potential utility for archaea to promote bioleaching of copper from refractory copper sulfide minerals. Bioleaching at thermophilic temperatures, above 60 °C, resulted in extraction of copper from chalcopyrite.

Nearly four decades after the original discovery of iron-oxidizing archaea (Batty and Rorke, 2005; du Plessis et al., 2007), knowledge of thermophilic archaea bioleaching of chalcopyrite concentrates was transferred to the engineering phase with demonstration of potential commercial applications occurring in 2003. The BioCop™ process, developed by BHP Billiton and successfully applied at prototype scale, employed acidophilic, iron-oxidizing archaea for bioleaching chalcopyrite concentrates in aerated stirred-tank reactor systems. The microbes used consisted of members of the genera *Sulfolobus*, *Metallosphaera* and *Acidianus*. The process operated at 78 °C, pH 1.5, 12% (w/w) pulp density with >98% copper recovery.

Primary mineral covellite – as distinguished from the more easily leached "blaubleinbender" form of covellite, which is a reaction product of chalcocite oxidation – is more amenable to thermophilic bioleaching than to mesophilic bioleaching (Acar et al., 2005). A crushed ore sample containing copper primarily as the mineral covellite was bioleached in columns at 20–23 °C, containing a consortium of *Acidithiobacillus*/*Leptospirillum*/*Sulfobacillus* species, and at 60–65 °C with the archaea *Acidianus* and *Metallospheara* species. Bioleaching for a period of 346 days resulted in copper extractions of 12 to 20% for the mesophilic bacteria and 62–65% for the thermophilic archaea. These results demonstrate the promise for large scale bioleaching of copper in heaps of refractory copper minerals.

Bioleaching of molybdenum from molybdenite was also demonstrated using *A. brierleyi* (Brierley and Murr, 1973). The mesophilic bioleaching bacteria *A. ferrooxidans* were believed to be ineffective for significant leaching of molybdenum due in part to inhibition by 5–90 mg Mo/l (Tuovinen et al., 1971). However, recent work has demonstrated bioleaching of molybdenite by *A. ferrooxidans* when solution redox potentials exceeded 750 mV to 800 mV (s.h.e.) (Olson and Clark, 2008). Under these conditions *A. ferrooxidans* is resistant to 4.4 g Mo/L. This work also demonstrates that variability of microbial

Table 2
Bioleaching copper from a chalcopyrite concentrate (modified from Brierley and Brierley, 1978)

Bioleach time [Days]	Copper leached at respective incubation temperatures [Percent]	
	22 °C	60 °C
30	10.9	39.5
60	12.7	89.7

Table 3
Thermophilic biooxidation of a refractory pyritic gold concentrate (modified from Hutchins et al., 1988)

Biooxidation pretreatment time [Days]	Iron bioleached [Percent]	Gold recovery [Percent]
0	0	0
2	14.5	19.7
10	35.5	47.7
17	59.8	74.2