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A Brief Note on the Heap Leaching Technologies for the Recovery of Valuable Metals

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Abstract: Heap leaching is a low-cost technology used in industrial mining to recover precious metals such as gold and uranium, along with several other highly sought after metals like copper, from their primary resources (ores and minerals). For many decades, there has been a growing demand for heap leaching due to its environmental benefits. Heap leaching provides mining operators with a benign, effective and economical solution for the environment and produces only minor emissions from furnaces. The cost of the heap leaching process is low, making this process an attractive option from a financial standpoint. Here, we shall present a brief review of the heap leaching process when applied to the extraction of different metals from primary resources (ores and minerals). This paper presents a roadmap to satisfy future national demands for rare earth elements (REEs). This heap leaching process is applicable for the recovery of REEs from secondary resources such as mining and coal residues. Heap leaching plays a significant role in the recovery of critical elements which are used in clean and green energy applications. In the mining sector, heap leaching is a distinguished method for the recovery of valuable/beneficial metals from low-quality ore. In the present study, we shall report briefly on the heap leaching technologies for valuable metal recovery with economic advantages.

Keywords: Heap Leaching; mining waste; recovery; valuable metals; rare earth; energy applications

1. Introduction

Heap leaching is one of the oldest and the most traditional mining process used to extract the valuable metals from specific minerals. Basically, this is a hydrometallurgical process in which the solution is applied for the dissolution of minerals from the ore that is used for the extraction of metals. Originally, heap leaching was practiced 500 years ago. Georgius Agricola published a book De Re Metallica in 1557 and reported that the heap leaching process was finished in a 40-day cycle [1]. Since the middle of the 16th century, heap leaching was practiced in Hungary for copper extraction. In 1969, gold heap leaching began in Nevada (birth place of modern heap leaching) and in the middle of the 20th century, the United States Bureau of Mines began applying this technology. Gold and silver heap leaching first began at Cortez in 1969. Currently, 37 different heap leaching operations are active worldwide for the production of gold, which is estimated to be around198 tons per year.

Currently, new heap leaching operations are successfully commissioned throughout the world with the goal of treating mine tailings and residue and to establish effective waste management facilities [2,3].In recent years, 50 major heap-leaching, solvent-extraction, electro winning operations have been established throughout the world, and approximately three million tons of copper have been recovered, representing roughly 16% total copper production [4]. The heap leaching technology developed thus far can be used for different types of ore. Advanced modeling studies and solid fundamentals of heap leaching technology could make the process more adaptable for increasingly composite ores [5].

Several factors are crucial for notable heap leaching operations, such as proper heap building and ore evaluations, efficient comminution methods, and feasible approaches to control the heap leaching process. There have been extensive reports and publications on current heap leach pad designs and construction practices [6]. Current heap leaching methods were developed according to the industrial requirements. For example, heap leach ore depths were increased from 50–60 ft. to 500 ft. This function is significant for controlling the economic efficiency, surface area availability and also for reducing the impact of mining reclamation on the environment. Heap leaching solution application rates are optimized for metal recovery with the minimal chemical consumption [7]. The heap leaching process is very simple and thus offers greater economic feasibility over more expensive technologies [8]. The motivation behind the use of heap leaching is financial feasibility.

The major advantage of the heap leaching method over conventional leaching and recovery techniques is that heap leaching consumes less than 0.3 ton of water for one ton of ore. Tank leaching normally operates as a continuous process within specially designed reactors. This approach is also known as a semi-closed system. Essentially, tank leaching is carried out in a set of tanks. In pressure leaching, finely ground ores are chemically treated at high pressures and temperatures within the reactors. The foremost application of the tank leaching method is the extraction of aluminum at low pressures and temperatures [9].The heap leaching process is obviously suitable method and has lot of advantages as mentioned above: however, as per the environmental concern it has some draw backs, such as time consumption, water loss, accidental leakages of pregnant leach solutions, slow heap leach kinetics, and acid mine drainage problems (sulfides).The present objectives of this paper are to provide information on the applications of a unique and versatile heap leaching process for rare earth extraction and to highlight the advantages and limitations of this process.

2. Heap Leaching of Mines

Industrial mining processes are the activities involved in the extraction of metals or minerals. A good example can be the classical production process of iron sulfate. In this process, iron pyrite was heaped up and the leachate coming from the heap was collected and boiled with iron resulting in the production of iron sulfate. The basic processes involved in heap leaching are ore crushing, spreading the crushed ore over HDPE or PVC geomembrane-lined pads, and spraying a leaching solvent like sulfuric acid or cyanide over the pads so that valuable minerals will dissolve into the pregnant solution. Metal recovery is then performed through precipitation, smelting or electro-winning and absorption methods.

Generally, low-grade ores of valuable metals like gold, silver, and platinum are mined from the surface of the earth or sometimes subsurface of the earth, pulverized into tiny particles, and collected on to a dense leach pad. The heap leaching process involves several steps. First, a leach solution is used to irrigate the heap. The second step is interaction with the ore particles. Third, the precious metal leaches out of the solution. Fourth, the pregnant solution is collected, and finally, draining of the tailing areas is done for metal extraction. Lime, Portland cement, coal fly ash, and bottom ash, or other materials are mixed with crushed ore for agglomeration. In a few cases, after pulverization, sulfide ores can be treated via chlorination, bio-oxidation, roasting and autoclaving methods prior to the heap leaching process. In gold leaching, two similar types of leaching pads are used to maintain permanent heap operations. A summary of leaching methods used for the extraction of various metals is shown in Table 1. Precious metal recovery by heap leaching [10], base metals from oxide ores [11], Zn [12], and gold recovery by heap bio oxidation. The main concern of this thesis was to understand the gold mineralizing process and the optimization of operational parameters during the bio oxidation process. Basically, the low-grade ore was oxidized via the biological heap method, and later it was utilized as a supplementary feed [13]. The heap leaching with computation process is a newly developed heap leaching methodology that combines analytical modeling and the Bernoulli type model to achieve a heap leaching scale up process. This method is very useful to optimize the heap leaching process (design, analysis, control and optimization) and also proposes optimal flow rates for the heap leaching process [14] of gold [15], platinum group metals and base metals [16] sequential heap leaching for platinum group metals [17], heap leaching with mathematical modeling for the extraction of copper was developed [18]. In this paper, the authors reported the heap leaching plan and design for copper leaching by the mathematical model named MINLP and BARON-GAMS solver. They studied different primary variables such as acid price, variable costs, and ore grade quality. These were highly effective on the production capacity of copper.

Table 1. Summary of leaching methods for the extraction of different metals with recovery efficiencies [10–29].

Method	Extraction Metal	Summary	Reference
Heap leaching	Precious metals from mineral fines	Leaching has been used principally in connection with low-grade copper ores or pit wastes.	Michael Kerr et al., 1998 [10]
Heap leaching	Base metals from oxide ores	75–82% of Nickel recovery was achieved in 160 days to 266 days, 90% Cobalt recovery was achieved in 14 days, Iron recovery (53.6%) was achieved in 198 days at ambient temperatures	Anthony et al., 2004 [11]
Heap leaching	Zn (Zinc)	The 95% of zinc recovery was possible in 16 days cycle at 25°C by column (heap) leaching.	Wen-qing et al., 2007 [12]
Heap leaching bio oxidation	Gold	49–61% of gold was recovery by bio oxidation process at 81°C. The bio oxidation process was for gold recovery was taken 150 days.	Wes K. Sherlock 2010 [13]
Heap leaching with computation process	Copper	71–73.5% of copper was recovery by developed a new heap leaching methodology with the combining analytical modelling at optimal flow rates.	Mario E. Mellado et al., 2011 [14]
Heap Leaching	Gold	30–95% of gold was recovery by best available technology heap leaching compared to other techniques.	Caner Zanbak., 2012 [15]
Heap leaching	Platinum group metals (PGMs) and base metals (BMs) from a low grade flotation concentrate of PGM concentrator plants.	The extractions of 52% Cu, 95% Ni and 85% Co were achieved in 30 days (65°C) by heap bioleach. If cyanide leach process (23°C) can be operated in 21 days, 20.3% Pt, 87% Pd and 46% Rh, if 50 days or more to achieve 50% platinum.	Mwase et al., 2012 [16]
Sequential heap leaching	Platinum group metals and particularly for palladium	At 65 °C, 93% Copper, 75% Ni and 53% Co extracted by bio heap leaching in the 304 days. By cyanide leach experiment, 57.8% Pt, 99.7% Pd and 90.3% Au was extracted at 50°C in 60 days.	Mwase et al., 2014 [17]
Heap leaching with mathematical modeling	copper	By the Mellado et al., method for the optimal design of heap leaching, 53–56% copper recovery was possible in a61–67 days.	Jorcy Y. Trujillo et al., 2014 [18]
Heap bioleaching	Cu, metal extracted from reduced inorganic sulfur compounds.	Over 60% of Cu, extraction was possible by bio heap leaching at 45 °C during the 30 –48 days.	Watling et al., 2015 [19]
Heap leaching	Copper from ore	73% of Cu recovery was achieved in 140 days at 25 °C.	Rautenbach, 2015 [22]
Heap leaching for rare earths extraction	Heavy rare earths and Yttrium	91.3% and 87.2% of Yttrium and dysprosium achieved by heap leaching for60 days, respectively, at room temperatures.	Pingitore Nicholas et al., 2016 [23]
Heap leaching with increasing flux rate	Gold	73–87% of gold extraction was achieved by using heap leach process with increasing flux rate in the 40 to60 days.	Ngantung, 2017 [24]
Heap leaching with the new model (MINLP) and GAMS software	Copper	69.7–76.7% of copper recovery was obtained from 19.5–43.5 days with the new mathematical modeling named mixed integer nonlinear programming (MINLP) including GAMS software (general algebraic modeling system).	Isis F. Hernández et al., 2017 [27]
Heap bioleaching	Nickel	60% recovery of nickel from the tailings for 110 days.	Anton Svetlov et al., 2017 [28]
Heap leaching with computational fluid dynamics model	Copper	55% of copper was recovered in the 700 days cycle at the temperatures from 12–45°C.	Diane McBride et al., 2018 [29]

It is possible to recover 60% of copper through heap bioleaching [19]. The authors discussed an appropriate pad design for high leaching efficiency in the brief reviews [20,21] on the heap pad designing criteria, pad characterization program, pad types, operational kinetics, material handling, and risk assessments. Finally, the authors concluded and recommended some technical tips for successful heap leaching facilities. Cu recovery of 73% was achieved in 140 days at 25°C [22]. In 60 days, 91.3% and 87.2% of Yttrium and dysprosium were achieved by heap leaching, respectively, at room temperatures [23]. The leaching processes with increasing flux rate for the gold recovery were also reported [24]. Some brief reviews reported on the heap leaching of copper and gold [25]. The main objective of this exclusive review paper is to understand the fundamental mechanism of the heap leaching process, as well the theoretical background of different heap leaching processes, global trend of commercial heap leaching operations, challenges, and the innovations and future directions of these process developments. This process is obviously suitable for low grade ores even if it has some draw backs. But it requires some comprehensive engineering concept developments for the higher efficiency of the product by heap leaching. Another brief review paper addressed a key technology for the recovery of valuable metals from low grade ores. The author covered heap leaching benefits, technical draw backs, economic feasibility, leaching kinetics, and environmental concerns [26].

Heap leaching with the new model (MINLP) and GAMS software [27], as well as the new model named mixed integer nonlinear programming (MINLP) including GAMS software (general algebraic modeling system) were utilized for the study of heap design and operational variables for metal recovery. It is one kind of a mathematical modeling applied for the copper leaching system. Recently, a heap bioleaching process was developed in Russia for the recovery of valuable copper and nickel from low-grade ore with a less expensive cost [28]. In Russia, the Murmansk region required urgent research action for the mining wastes. In this region they developed the technology for the recovery of valuable copper and nickel from low-grade ore. During these mining activities, lots of wastes were deposited, so bio heap leaching technology was developed for the recovery of metals from ores with less expensive cost. Heap leaching with the computational fluid dynamics (CFD)model [29] can analyze the heap design, operational parameters, optimization analysis and environmental conditions etc.

In the heap leaching process, initially the ore is pulverized and accumulated before it is placed on the heap in order to increase the mobility of the heap, as well as to maintain a high pH. Agglomeration involves the merging of the pulverized ore with binding material like ash, lime, Portland cement, or other materials. In few cases, pretreatment of sulfide ores by bio-oxidation, autoclaving, roasting, or chlorination before heap leaching. There are two kinds of pad that are used in gold heap leaching, depending on whether the spent ore is removed or not: permanent heap construction on a pad and on-off pads. The former is the one which the leached ore is not removed from the pad and the latter has being where the spent ore is removed, and another fresh ore is allowed to be placed on.

2.1. Heap Leaching Advantages and Economic factors

Heap leaching has several advantages and economic benefits. These include low capital requirements and low operating costs [1]; the absence of a milling step for crushing and agglomeration; the simplicity of atmospheric leaching; possible use for the treatment of moderate (medium) grade ores, (pebble size is ~31 mm with round shape) [30], wastes and few deposits; and omission of liquid-solid separation step for counter-current operations, when metal tensor can do accumulate due to the use of the recycling solution over the heaps. Some ores which require crushing, agglomeration, and conveyor stacking may require little additional cost. The capital expenditures (CAPEX) and operating expenses (OPEX) of copper [31], gold [32], and silver [33] by heap leaching, tank leaching of copper [34], gold [35], and silver [36] and autoclave leaching of copper [37], gold [38], and silver [39] are expressed in million dollars per ton of ore in Table 2.

Table 2. Comparison of capital expenditures (CAPEX) and operating expenses (OPEX) of copper, gold, and silver by heap leaching, tank leaching and autoclave methods.

Metal Name	Heap Leaching Capital Expenditure (CAPEX) US$/t ore	Heap Leaching Operating Expenditure (OPEX) US$/t ore	Tank Leaching Capital Expenditure (CAPEX) US$/t ore	Tank Leaching Operating Expenditure (OPEX) US$/t ore	Autoclave Leaching Capital Expenditure (CAPEX) US$/t ore	Autoclave Leaching Operating Expenditure (OPEX) US$/t ore
Copper	29.5	4.6	25	66	75	19
Gold	22	4.51	40.9	22.28	492	8.20
Silver	22.50	14.87	40.9	35.96	17.40	82

2.2. Heap Leaching of gold and silver

Heap leaching is a very significant and common process in the copper and gold industry. It is very economical and useful for treating a wide range of low-grade ore bodies on a large scale. The simple heap leaching process is very competitive with other expensive laterite technologies. The Bureau of Mines reported the development of a gold ore heap leaching process which used a diluted cyanide solution for the gold and silver recovery from pregnant effluents by a carbon adsorption-desorption process [40]. Hazardous waste engineering research laboratories submitted a report to the Environmental Protection Agency in the USA describing the great distribution and operational capabilities of the gold/silver heap leaching process and the potential environmental impact and management practices to minimize potential environmental releases [41]. The basic processes involved in heap leaching are crushing the ore, spreading the crushed ore over HDPE or PVC geomembrane-lined pads, spraying leaching solvent like sulphuric acid or cyanide over the pads and then valuable minerals will dissolve into the pregnant solution. Metal recovery is then performed through precipitation, smelting or electro-winning and absorption methods [42]. Figure 1 shows a flow chart of a gold heap leach operation [43]. A hydrometallurgical process has been designed for the amenable gold heap leaching from low-grade gold ore [44,45].

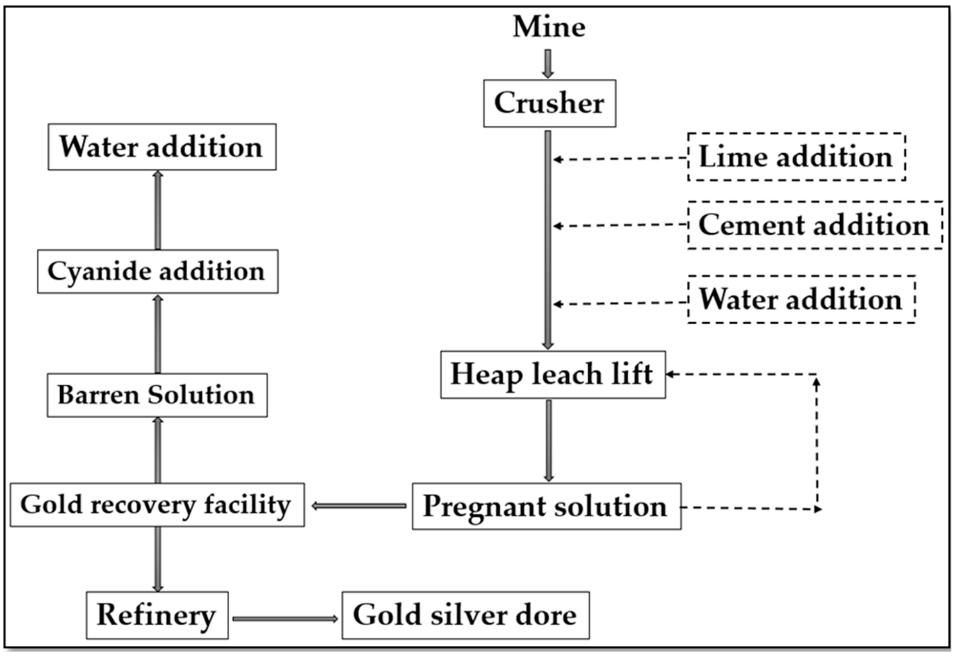

Figure 1. Chart of a gold heap-leach operation (adopted and modified from the reference 43).

2.3. Heap Leaching of Copper

There are numerous reports available on copper heap leaching from copper ore [46,47]. Some researchers have used heap leaching technology for the recovery of copper by using sodium nitrate as an oxidizing agent. The pH of the heap was maintained at pH < 1.7 [48]. Other investigations reported the heap leaching process of copper from diesel deposits [49]. The non-ionic surfactant EVD61549 (a wetting agent) was used to increase the copper heap leaching efficiency [50]. Heap leaching of waste copper ores from Volkovskoe deposits has also been considered for sulphuric acid leaching (25–75 kg/t ore). Over a period of three months, the copper leaching efficiency reached 76–78% overall. The copper recovery efficiency increased with an increase in the leaching time [51].

2.4. Heap Leaching of Uranium

Large-scale uranium heap leaching activities have operated since the 1970s and 1980s. Historically, sources of uranium ore contain ≥0.05% of uranium/thorium. In the 1950s and 1960s, ores containing less than 0.05% uranium were periodically refined in small heaps. There are three methods used for uranium recovery, namely: traditional milling, in situ recovery (ISR), and heap leaching methods. In the USA, heap leaching technology is widely used for the recovery of uranium. A rancher exploration and development corporation in Colorado was operated between 1977 and 1979 [52]. Some investigations reported bacterial leaching processes. Generally, problems arose during the oxidation of U^{+4} species, and approximately 70% could be recovered. Heap leaching technologies eliminate grinding, tank leaching and the solid/liquid separation step, and it is likely applicable to many types of low-grade uranium ore of many types. The conventional leach times are between one and six months. Recently, researchers reported the analytical models for the heap leaching by global sensitivity analysis and uncertainty analysis [53]. Figure 2 shows a flow diagram of gold, copper and uranium heap leach operation flow sheets [54].

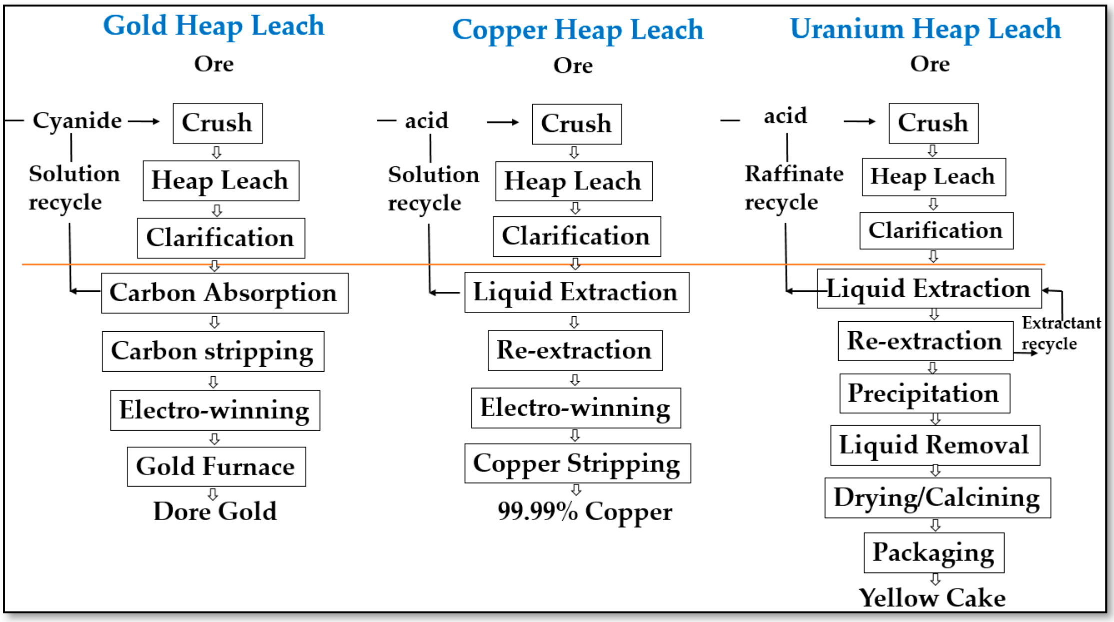

Figure 2. Flow diagrams of heap leaching processes of gold, copper, and uranium (adopted and modified from reference 54).

3. Rare Earth Elements Recovery by Heap Leaching

Recently, rare earth appliances are significantly increased for new products. During the past 20 years, REEs have many new applications such as clean energy, petroleum refining, electronics, and automobiles. Military applications have also arisen as these materials are widely used in communication systems, avionics, lasers, precision-guided munitions, radar systems, satellites and night vision equipment (Figure 3).

Figure 3. Heap leaching for rare earth recovery.

The assessment and source of REEs are in much interest, and advanced technologies are therefore required for the recovery of critical rare earths from waste residue via the heap leaching process. In the second generation of leaching technology, heap leaching with $(NH4)_2SO_4$ in the early 1980s was used to enhance the product purity to more than 92% for the total rare earth oxide content. During the washing process, the solid-to-liquid ratio was maintained at approximately 0.6:1 build upon the leaching time and heap size. Leaching times ranging from 100 to 320 h are more beneficial for rare earth extraction, with rates up to 90% realized [55].

Ion-adsorption clays from various origins or ores are rich sources of rare earths and the recovery process by in-situ leaching [56,57] and heap leaching [58]. 80% of the rare earths such as Y, Nd, Eu, Tb, and Dy were recovered by several process including physical separation, bio oxidation, heap leaching, precipitation and solvent extraction respectively. In 250 days, 85% of there're earths were leached with pH 0. When pH was increased to 3, rare earth recovery was observed to increase by two-fold. Texas rare earth resources independently confirmed a 79.9% recovery rate by the heap leaching process [59]. Recently, heap leaching was applied for the recovery of the yttrium, from the ore yttrofluorite. Yttrium-bearing fluorite at Round Top Mountain is a rich source of Yttrium, and other heavy rare earth elements were recovered by the heap leaching process. In 60 days, 91.3% and 87.2% of Yttrium and dysprosium were achieved by heap leaching, respectively, at room temperatures [23].

Recently, the National Energy Technology Laboratory (NETL) funded the University of Utah and Virginia Technology for the extraction of rare earths from coal refuse by heap leaching, along with other sequential processes such as coal processing, bio oxidation, solution treatment, solvent extraction, and precipitation technologies respectively [60].

4. Conclusions

Heap leaching technologies have been profitably adopted for the recovery of highly sought after metals. Worldwide, a huge interest in heap leaching projects has-been observed for the recovery of precious metals. Heap leaching is an essential metallurgical process which has demonstrated a strong potential to reduce costs and liberate metals from challenging deposits. Nowadays, prices for all precious metals and rare earths are increasing rapidly due to the continuous demand in green technology applications. Heap leaching is a more economic process than any other conventional method, and exceptionally so for the recovery of precious metals from low grade ore.

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