The present work was submitted to the Faculty of Engineering

Planning, Monitoring, Closure, Renaturation, and Reclamation of Dump and Heap Leaching Operations under Special Consideration of Environmental Risks

Bachelor Thesis

by

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Ulaanbaatar/Nalaikh, 05/16/2022

Statutory Declaration

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I hereby affirm in lieu of an oath that I provided the submitted bachelor thesis

Planning, Monitoring, Closure, Renaturation, and Reclamation of Dump and Heap Leaching Operations under Special Consideration of Environmental Risks

I did not use any sources other than those stated. In case that the work is additionally submitted on a data medium, I declare that the written and the electronic form are completely identical. The work was not submitted in the same or similar form to any examination authority.

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Abstract

Copper is a metal that has numerous applications in our surroundings and industrial sector due to its physical and chemical properties whereas potentially pertinent applications of gold are extended with forthcoming and outstanding nanotechnology where gold nanoparticles play role in biological sciences, chemical platforms, and materials science. Absence of high-grade deposits results in developing technologies which recover newly found or old stockpiled low grade, complex ores. Heap and dump leaching processes are designated for the low-grade ore since capital cost is relatively low than other percolation leaching processes.

In this thesis paper, concepts and current technologies of heap and dump leaching processes are studied within the outline of concept of the process, design of the construction, and the modern closure technologies with special consideration of environmental factors and risks. To set a baseline of the chemicals and pollutants, the relevant legal environment and standards were introduced in the literature review.

Percolation leaches mine operation and closure is the relatively new concept in Mongolia, in which the first tank leach processing plant has started the construction in 2002 and the commercial production in March 2004. Therefore, mine practices and cases of Mongolia and other foreign countries were selected based on the PESTLE analysis and investigated in advance to present the importance of closure management plan. Case studies are carefully chosen in prior of similar mine operation and closed mine accident. It was clarified from the studies that mine closure should be planned in advance of the operation, closure fund must be guaranteed, and the post closure risks have to be considered.

Acknowledgement

This project would not have been possible without the support of many people. Many thanks to my supervisor, Prof. Dr. Thomas Hollenberg, who provided me an opportunity to work on this thesis, guided me to make the thesis concise and reasonable throughout the progress. Also, thanks to another supervisor Ms. Munkhzaya for her effort to support me with the essential information as well as advice and encouragement with a perfect blend of insight and care.

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Abbreviation

AARL	Anglo American Research Laboratories
AMD	Acid Mine Drainage
ARD	Acid Rock Drainage
ATO	Altan Tsagaan Ovoo
AuEq	Gold equivalent
CIL	Carbon-in-Leach
CIP	Carbon-in-Pulp
HDPE	High-density polyethylene
LLDPE	Linear low-density polyethylene
PLS	Pregnant leach solution
PVC	Polyvinyl chloride
ROM	Run of the mine
SAG	semi autogenous
UN	United Nations

1 Introduction

1.1 Background

Significance of copper

Copper is a metal that universally used in our surroundings such as building construction, electrical and electronic products, industrial machinery and equipment, transportation, as well as consumer and general products as shown in Figure 1 due to its feature of being outstanding heat and electricity conductor, corrosion resistant, and antimicrobial in addition to malleable and ductile metallic properties.

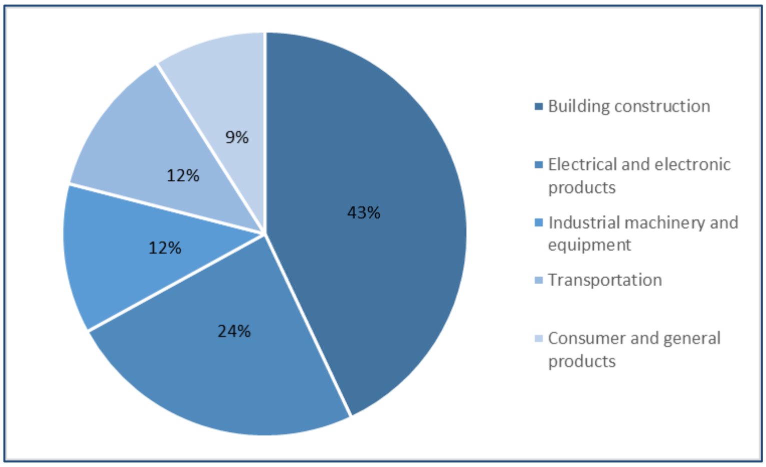

Figure 1. Consumption in the United States (1)

The main sources of naturally occurring copper in the Earth's crust can be divided into four distinct groups as below:

1. **Sulfide deposits** which include chalcopyrite, bornite, chalcocite, and covellite
2. **Carbonate deposits**, the well-known representatives are azurite and malachite
3. **Silicate deposits** such as chrysocolla and dioptase
4. **Pure native** copper

The most abundant type of copper bearing mineral is chalcopyrite which constitutes for approximately 70% of world's known copper reserves. A face-centered tetragonal lattice-structural configuration of the mineral makes chalcopyrite the most stable and refractory mineral to hydrometallurgical processing (2).

According to U.S. Geological Survey (USGS) and International Copper Study Group (ICSG), there are identified resource of 2,100 million tons (Mt) and undiscovered resource of 3,500 Mt of copper, whereas reserves, annual refinery production, and annual mine production are equal to 880 Mt, 26 Mt, and 21 Mt, accordingly as of 2021.

Table 1 shows mine production of the last 10 years by countries. The data was revised by USGS in ways of revising company and/or Government information. The mine production has a trend of increase in the capacity, but it is negatively influenced by COVID-19 pandemic in 2020. By the end of 2020, Chile is the biggest producer that has mined 5.73 billion tons of copper followed by Peru and China (3).

	Mine production, thousand tons									
	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
United States	1,110	1,170	1,250	1,360	1,380	1,430	1,260	1,220	1,260	1,200
Australia	958	958	990	970	971	948	860	920	934	885
Canada	566	579	632	696	697	708			573	585
Chile	5,260	5,430	5,780	5,750	5,760	5,550	5,500	5,830	5,790	5,730
China	1,310	1,630	1,600	1,760	1,710	1,900	1,710	1,590	1,680	1,720
Congo (Kinshasa)	520	600	970	1,030	1,020	846	1,090	1,230	1,290	1,600
Indonesia	543	360	504			727	622	651		505
Kazakhstan	417	424	446					603	562	552
Mexico	443	440	480	515	594	752	742	751	715	733
Peru	1,240	1,300	1,380	1,380	1,700	2,350	2,450	2,440	2,460	2,150
Poland	427	427	429						399	393
Russia	713	883	833	742	732		705	751	801	810
Zambia	668	690	760	708	712	763	794	854	797	853
Other countries	1,970	2,000	2,200	3,600	3,800	4,160	4,250	3,540	3,100	2,840
World total (rounded)	**16,100**	**16,900**	**18,300**	**18,700**	**19,100**	**20,100**	**20,000**	**20,400**	**20,400**	**20,600**

Table 1. World copper mine production (3–12)

Significance of gold

Gold has properties of lustrous color, resistance to tarnishing, excellent conducting, very malleable and highly ductile so that is consumed in jewelry, industrial applications, electrics, electronics, and in official coins and medals and imitation coins. Furthermore, potentially pertinent applications of gold are extended with forthcoming and outstanding nanotechnology where gold nanoparticles play role in biological sciences, chemical platforms, and materials science (13).

Classification of gold ore types can be arranged from free-milling to refractory in order of placers, quartz vein-lode ores, oxidized ores, silver-rich ores, copper sulfide ores, iron oxide copper-gold ores, iron sulfide ores, arsenic sulfide ores, antimony sulfide ores, bismuth sulfide ores, telluride ores, as well as carbonaceous sulfide ores (14). Moreover, gold is classified by forms and carriers into three major groups in the same paper such as:

- **microscopic gold** (visible gold), gold alloys – including native gold (Au), electrum (Au, Ag), kustelite (Ag, Au), auricupride (Cu_3Au), tetraauricupride

(CuAu), gold tellurides – calaverite ($AuTe_2$), gold antimonide – auristibite ($AuSb_2$), gold bismuthide – maldonite (Au_2Bi)

- **submicroscopic gold** (invisible gold), solid solution gold and colloidal gold – arsenopyrite (FeAsS), pyrite (FeS_2), marcasite (FeS_2), FeOx (Fe_3O_4 – Fe_2O_3), loellingite ($FeAs_2$), chalcopyrite ($CuFeS_2$), realgar (AsS), enargite (Cu_3AsS_4), acanthite (Ag_2S), as well as clay minerals
- **surface-bound gold** (adsorbed gold), metallic gold and gold complex – FeOx (Fe_3O_4 – Fe_2O_3), stained quartz, carbonaceous matter (C-matter), graphite, arsenopyrite (FeAsS), pyrite (FeS_2), clay minerals, wood chips, and activated carbon

As proposed in (15), it is reasonable to divide and assess four types of gold deposit based on grade, mineralogical feature, and follow-up valuable metals which determines the processing technique as follows:

1. **Free milling** in which gold can be economically processed by direct cyanidation and carbon in pulp/carbon in leach (CIP/CIL) or Merrill-Crowe zinc cementation.
2. **Heap-leachable** where heap leaching is economical instead of tank cyanidation.
3. **Concentrate sale** in which gold as co-product are also sold within the concentrate that can be separated and/or enriched by different process systems.
4. **Refractory** gold ores require preprocessing before leaching or recovery since metallurgical testwork of simple cyanidation results in low recovery (16).

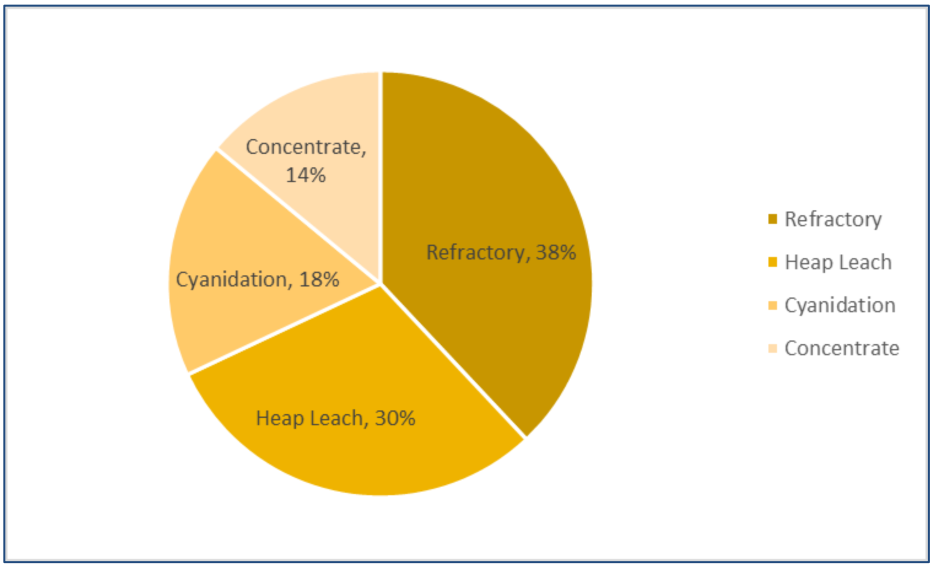

Figure 2. Gold processing types of top twenty global gold producers in 2011 (17)

Top twenty gold producing mines are summarized in the Figure 2. Gold processing types of top twenty global gold producers in 2011 (17) by Adams. In refractory segment, 21%

was produced by roasting, 10% by pressure oxidation (POX), 5% by ultra-fine grinding (UFG), and 3% by bacterial oxidation bioleaching.

As stated in the report of U.S. Geological Survey, there are gold resources of 33,000 tons in which 15,000 tons of identified and 18,000 tons of undiscovered resources in 2021 (3). Almost 25% of undiscovered gold is reported to porphyry copper deposits. By the end of 2020, China is the biggest producer of gold mine production followed by Australia, Russia, United States, and Canada.

	Mine production, thousand tons									
	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
United States	234	235	230	210	214	222	237	226	200	193
Australia	258	250	265	274	278	290	301	315	325	328
Brazil	62	65	71	80	81	85	80	85	90	78
Canada	97	104	124	152	153	165	164	183	175	170
China	362	403	430	450	450	453	426	401	380	365
Ghana	80	87	90	91	88	79	128	127	142	125
Indonesia	96	59	61	69	97	80	75	135	139	86
Kazakhstan						69	85	100	107	63
Mexico	84	97	98	118	135	111	126	117	111	102
Papua New Guinea	66	53	57	53	60	62	64	67	74	54
Peru	164	161	151	140	145	153	151	143	128	87
Russia	200	218	230	247	252	253	270	311	305	305
South Africa	181	160	160	152	145	145	137	117	105	96
Uzbekistan	91	93	98	100	102	102	104	104	93	101
Other countries	685	705	735	858	897	840	883	869	927	874
World total (rounded)	**2,660**	**2,690**	**2,800**	**2,990**	**3,100**	**3,110**	**3,230**	**3,300**	**3,300**	**3,030**

Table 2. World gold mine production (3–12)

A remarkable note for the world gold mine production is that the twelve gold-mine producing countries accounted for 69% of global production besides behind twelve countries were responsible for 20% of global gold production (18). World gold mine production increases year by year, but COVID-19 pandemic has negatively affected the production in 2020 which has had a consequence in a drop of the constantly increasing mine production. However, some countries could maintain to keep the increase in that year as shown in Table 2.

Environment and mining

Although mining plays an important role in our modern technological society, it is not well-regarded by the general public for three reasons: a lack of public understanding of the source of all of our material goods, the tendency of the news media to focus on negative stories about mining, and the visible consequences of mining operations (19). The mining sector has a lot of environmental consequences that can be problematic. Hazards from ancient mine workings, heavy metals leached from old mine dumps, dust blown from old mine dumps and tailings impoundments, tailings dam collapse, radioactivity of some mine wastes, and acid mine drainage output from old mines are among them. These occurrences can have a significant influence in some areas.

The United Nations (UN) has set seventeen sustainable development goals in 2015 with the deadline of 2030. Under the goals, mining operations will be required to extract responsibly, waste less, utilize safer procedures, adopt innovative sustainable technology, encourage increased community wellbeing, reduce emissions, and enhance environmental stewardship.

It is true that today's most well-known mining corporations make a concerted effort to project a leading image to the public in terms of environmental protection and other operations. They focus on producing minerals with the minimum amount of environmental impact, to ensure the safety and health of their employees, to have a good impact on the geographic locations in which they operate, and to assist their neighbors. They believe in the notion of mineral sustainability and work hard to raise public awareness about their role in life, how they provide to public welfare, and how well they are striving to create a better society.

The most visible environmental impacts are the change, often near-total devastation, of the mine site's natural landscape. Topsoil removal can leave large regions naked for years. The arrangement of barren rock results in huge constructions that are prone to breakdown. Natural terrain changes and rock deposits put a strain on the aquatic environment, especially in locations where water is scarce, as is the case in many developing nations (20).

1.2 Objective of the study

Copper hydrometallurgical process development have been focusing on completely leaching chalcopyrite in a short amount of time with elemental sulfur yield as an alternative for pyrometallurgical techniques (21).

Gold extracting technologies have been improved since gold demand and price moderately increase for the last 40 years (22). Although alkaline solution-based cyanidation process is considered both economically and technologically viable, alternative lixiviant is actively developed to find practical substituents due to environmental issues regarding the cyanide leaching related to disposal issue (23,24). Not only the current lixiviant choice, but other developments have also been made in retaliation to shrinking high-grade deposits, shift towards underground mining, increasing complexity of treatment, as well as environmental constraints concerns (24,25).

Advanced extraction technologies allow the research and mining companies to extract the precious metal more economically and efficiently from ores which had been considered uneconomical grade (24). Therefore, it is crucial to utilize gold resource and develop effective environmental protection (23).

The primary purpose of this study is to develop and provide comprehensive as well as simple review and recommendations of heap and dump leaching of copper and/or gold without discarding the environmental aspects to the further research and mining companies, especially in Mongolia.

Research Questions:

Question 1: Is heap leaching more harmless to the environment than dump leaching?

Question 2: What technologies are developed in heap and dump leaching?

Question 3: What legal documents and requirements regarding mining and environment are established and implemented in Mongolia?

Question 4: Can a closure of leach mine be environmentally safe?

Question 5: Is it achievable to adopt technologies from similar foreign mines to Mongolia?

Hypotheses / assumptions:

H1: Heap leaching is more suitable process when environmental risks are strictly concerned compared to dump leach process.

H2: Construction, operation, and closure of heap leaching process can be allowed under the laws and standards of Mongolia.

H3: Closure of heap leach process can avoid environmental danger if measures and actions for environment are carefully taken from planning to closure stages.

The key goal can be achieved in the following ways:

- To investigate the currently used innovative methods of the process
- To summarize Mongolian leaching practices and international case studies
- To research leaching related mine closure issues and their solutions

This study focuses on reviewing different literatures, data, and case studies regarding the heap and dump leaching process of copper and/or gold ores from planning to closure that can be used by current operating and/or upcoming mining companies.

1.3 Methodology

Aim to conduct research on the heap leaching process is to explore principles of the leaching, possibility of the process in Mongolia, closure methods for emerging environmental risks, and applied technologies in foreign comparable mines in order to provide sufficient review on research.

The boundary of the thesis will be limited by heap and dump leach processes of copper and gold metals since these processes have been widely developing in Mongolia while bringing some threats to environment and surrounding eco systems. The author is not aware of economical aspect of heap and dump leaching process. Furthermore, review on dump leaching is only used for direct comparisons with heap leach process, technologies and other views on such process are neglected in this study.

In this thesis, firstly qualitative literature review will be done by which current technologies regarding percolation leach processes especially heap and dump leaching. With same qualitative data collection method, Mongolian major leach mines and legal environment regarding the process will be studied to determine legally confirmed environmental requirements. In addition, SWOT analysis (strengths, weaknesses, opportunities, and threats) will be applied to exaggerate the technologies in advance.

To describe, compare, evaluate, and understand various aspects with regard to the leaching mines, embedded case study method for research was carefully chosen to examine foreign mines in advance. The progress will start with selection of cases, develop the mine related framework, as well as describe and analyze the case. The analysis will be made with multiple case studies to compare and clarify distinct aspects of the research problems. In addition to the descriptive analysis, PESTLE analysis (political, economic, social, technological, legal, environmental) will be used to set criterion for choosing cases for research.

2 Literature review

2.1 Heap and Dump leaching of copper and gold ore

Leaching process is that applies percolation process of leaching agent, also known as solvent or lixiviant, selectively extracting valuable metals from minerals. The process was firstly introduced by leaching copper in 16th century in Germany and Spain. Deposit and ore type often determines the following percolation leaching types (26):

- In situ leaching (Under Ground)
- Dump leaching (Run of Mine ore)
- Heap leaching (Crushed and/or Agglomerated ore)
- Vat leaching (Ore or Concentrates)
- Agglomerated fines heap leaching (Ore or Concentrates)

However, only dump and heap leaching will be studied in this paper considering its advantages such as low capital risk and cost, suitable for insufficient reserves and/or low-grade ore bodies, and equal or higher percentage recovery as stated by Kappes (27) and Table 3.

Advantages	Disadvantages
Low capital and operating cost	Low recovery (compared to agitated leaching) and long leaching time
Quick and easy installation	High caution of solution treatment
Low energy requirements	Large area
Low grade ores – wastes and small deposits	Lengthy large-scale test required for design
Unity in tailing disposal	High latency in process control
Less water requirement compared to mechanical processing	Closure issues in the long time
Integration with other processes is possible	Evaporation of water

Table 3. Advantages and disadvantages of heap leaching (28)

Heap leaching is the desirable method for recovering values from especially low-grade ores in the industry of copper and gold (29). Heap leaching is widely known for its low capital cost and cut of high intensity energy consuming comminution process.

Its practices have been significantly developed over the past 45 years, but selection of pad materials, sprinkling systems, and stacker constructions were often discarded as a tool for reducing capital cost of the operation (30).

Typical integrated flowsheet of copper oxide hydrometallurgical process is demonstrated in Figure 3. Ore is separated by its grade into two separate groups; high grade ore is transported into crushing stages whereas low grade ore is dumped and managed with acid and treated leachate from raffinate. In the agglomeration stage, acid and low-grade pregnant leach solution from dump are added and delivered to the leach pad in which fully treated ore is leached with leachate. Pregnant leach solution from the pad goes into solvent extraction stage from which raffinate goes to a solution pond and solute is treated with electrowinning stage to be produced as a cathode copper. From the raffinate pond, both main and accommodating leaching process respectively on leach pad and dump are fed with acid-treated leachate.

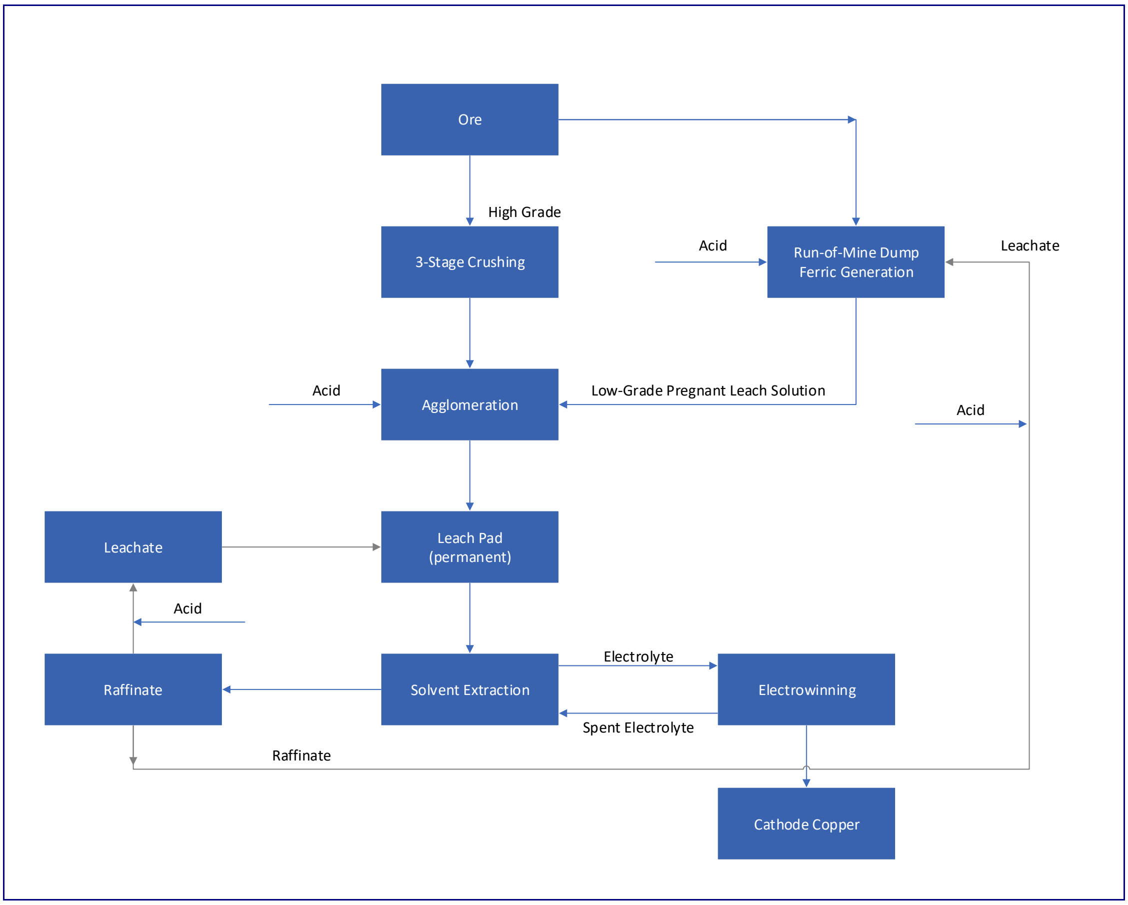

Figure 3. Hydrometallurgical flow process (31)

On the other hand, dump leaching differs from the heap leach process with larger particle sizes of bed, and non-comminuted and -agglomerated ores, as well as typical higher lifts as compared in Table 4.

.

	Particle size (P80 mm)	Crushed	Agglomeration	Irrigation rates (Lm-2h-1)	Lift height (m)	Leach time (Years)	Recovery (Typical %)
Heap leach	100-5 mm	Yes	Mostly	2-15	2-10 m	Cu: 1-4, Au: 0.1-2	40-97
Dump leach	1000-30 mm	No	No	2-15	8-75 m	Cu>10, Au: 2-6	20-85

Table 4. Leaching types and typical criteria (28)

2.2 State of the art of the process

2.2.1 Concept of leaching process

To conceptualize the process of leaching, solution and gas flows, diffusion of solution between particles, solute-mineral reactions, curing of solution, as well as test works are described in this third level subsection.

2.2.1.1 Flows in heap

The primary flows in heap leaching process can be divided into two groups as solution and air flow. There are two types of solution as follows:

- Stagnant solution – lies in inner crevices and in the pores by saturating these within ore bed. The liquid film of trapped solution surrounding ore particles is a critical place for the leaching processes where dissolution of metals takes place and diffuses to flowing liquid. The parameters of ore and solution which affects the solution are shape, agglomeration, size, and contact angle.
- Flowing liquid – drains through pores and small tubes of the bed by precipitously filling and flooding influenced by properties of bed as well as liquid and gas flow rate. The flow conducts mass transfer of dissolved minerals in the heap.

Air flow is canaling through unsaturated zones in which permeability of stacked ore is high. It might cause oxygen deficiency in flooded low permeability zones. Its flowing pattern and mass transfers are sometimes restricted by the flowing liquid. The flow is essential to provide oxygen to the chemical reaction (28).

Tortuosity is often introduced in modeling of leaching flow since it is an indispensable intrinsic property of flow through porous material. By definition, it is the ratio of actual length of flow path and projection of flow path. Robertson et al. (32) suggested to use the Carmen-Kozeny equation to evaluate the tortuosity for modeling which involves surface area of particles derived from the particle size distribution assuming the particles are sphere shaped. The recent study (33) modelled velocity and pressure distribution by using coupled numerical modeling and image processing of pore flow approach which applies Creeping equation, predicted tortuosity, and proved that these fluid properties highly depend on shapes, arrangements of particles, as well as bulk voidage in bed – implied from particle porosity, experienced by column test in laboratory. The same approach was applied in the same research in heap for predicting seepage, pooling, and path of flows.

2.2.1.2 Solute diffusion between particles

Porous medium allows leaching agent to firstly diffuse into ore, react with metal bearing minerals, then metallic complexes diffuse into the solution back. The transportation results in both physical and chemical non-equilibrium in the place, and drainage layer is prepared to collect dissolved and diffused solution from the nonideal flow and solute transport. Interparticle diffusion is eligible when the diffusion between flowing and immobile solutions are not sufficient for the process (28).

2.2.1.3 Chemical reactions occurred between solute and mineral

Designated ore types studied in this paper can be divided into three diverse groups, in particular, copper oxides, copper sulfides and leachable gold. Acid dissolves copper oxide when solution acidity or alkalinity, also known as pH of solution, is regulated whereas oxidative dissolution is introduced for copper sulfides. Acidic sulfate leach solution is efficient in dissolving the oxide minerals. Mineral grains, ore fragments, or a major portion of the heap create Eh-high pH microenvironments in which acid-oxidizing conditions might occur with elevation of temperature caused by self-heating oxidation. The early leached structures would be iron oxide, hydroxide, sulfate, sulfide, and silicate minerals (28).

Equation 1. Copper oxide minerals leaching in sulfuric acid

[1] $$Cu_2(OH)_2CO_3 + 2H_2SO_4 \rightarrow 2CuSO_4 + CO_2 + 3H_2O$$

[2] $$Cu_3(OH)_2CO_3 + 3H_2SO_4 \rightarrow 3CuSO_4 + 2CO_2 + 4H_2O$$

[3] $$CuO + H_2SO_4 \rightarrow CuSO_4 + H_2O$$

[4] $$Cu_2O + H_2SO_4 \rightarrow Cu + CuSO_4 + H_2O$$

[5] $$Cu_3SiO_3 \cdot 2H_2O + H_2SO_4 \rightarrow CuSO_4 + SiO_2 + 3H_2O$$

[6] $$Cu_4(SO_4)(OH)_6 + 3H_2SO_4 \rightarrow 4CuSO_4 + 6H_2O$$

As far as studying hydrometallurgical treatment, leaching with proper lixiviant is considered as the first step of the process; sulfuric acid is the most practical and adaptable choice for copper oxide ores (34). The oxide ores, malachite ($Cu_2(OH)_2CO_3$), azurite ($Cu_3(OH)_2CO_3$), tenorite (CuO), cuprite (Cu_2O), chrysocolla ($(Cu,Al)_2H_2Si_2O_5(OH)_4 \cdot n(H_2O)$), and brochantite ($Cu_4(SO_4)(OH)_6$) demonstrated in

Equation 1 reacts with sulfuric acid, the typical products are copper sulfate, water, as well as oxides of carbon and silicon.

Equation 2. Leaching reaction of gold with cyanide

$$4Au + 8CN^{-} + O_2 + 2H_2O \rightarrow 4Au(CN)^{-} + 4(OH)^{-}$$

Alkali solution involving ligand-based dissolution is used for gold particularly in cyanide solution. The qualification of gold for this dissolution must be oxidized and it forms to stable complex ion of cyanide gold and hydrogen peroxide with addition of suitable complexing agent. Other alternative agents include sodium bisulfide, thiosulfate, thiocyanate, thiourea, hypochlorite, bromide, and iodide solutions (28).

Furthermore, the oxidation reactions of sulfide minerals triggered either by oxygen, ferric ions, or microbial actions. In the ambient temperature, ferric ion contributes 100 to 1000 times faster oxidizes sulfide grain than direct application of oxygen. A process – ferric iron and protons constitute the reactants of oxidation – is integrated with a leaching agent to achieve a bioleach reaction (28).

Equation 3. Principle mechanism of bioleaching (35)

[1] $4Fe^{2} + O_2 + 4H^{+} \rightarrow 4Fe^{3+} + 2H_2O$

[2] $Cu_2S + 1.6Fe^{3+} \rightarrow 0.8Cu^{2+} + 1.6Fe^{2+} + (Cu_{1.2}S)$

[3] $(Cu_{1.2}S) + 2.4Fe^{3+} \rightarrow 1.2Cu^{2+} + 2.4Fe^{2+} + S^{0}$

[4] $2FeS_2 + 15O_2 + 2H_2O \rightarrow 2Fe_2(SO_4)_3 + 2H_2SO_4$

[5] $2S^{0} + 3O_2 + 2H_2O \rightarrow 2H_2SO_4$

A chemical equation for micro-organismic reaction prompted by oxidation of ferric or ferrous ions, developed for copper recovery, is presented in Equation 3-1, two-stage mechanism of ferric ion caused chalcocite leaching is demonstrated in Equation 3-2 and Equation 3-3, oxygen from heap aeration comes as Equation 3-4, and sulfuric acid of feed either derives from bio oxidation of pyrite as Equation 3-4 or elemental sulfur Equation 3-5 (35). Compared to tank leaching, such reaction factors as temperature, pH, as well as presence of oxygen and carbon dioxide cannot be effectively controlled for implementing bio-oxidation process.

2.2.2 Design

To cover heap leach design, a geotechnical and containment perspectives such as equipment loads, presence of water and local terrain.

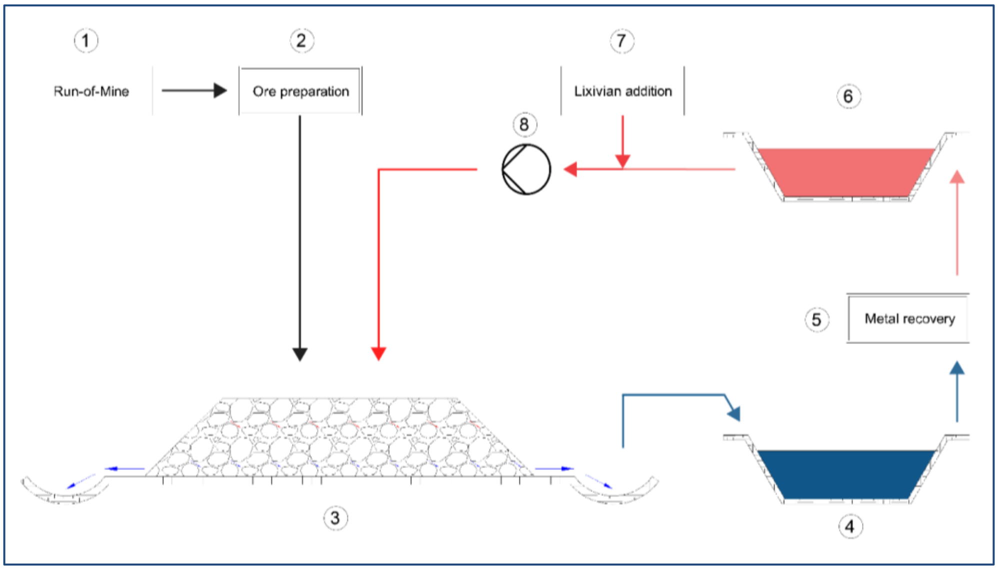

Figure 4. Generalized flowsheet of heap leach operation

As shown in Figure 4, heap leaching operation begins with [2] ore preparation from [1] run-of-mine, then piles ores on [3] the impermeable pad, lixiviant is added with sprinkling system and percolates through the stockpiles, then collected to [4] a pregnant solution pond. Pregnant leaching solution is transferred to [5] the refinery plant in which metal is recovered and moved to [6] the barren solution pond. From the pond, the solution is treated with [7] lixiviant addition and [8] applied to the heap in circular flow.

2.2.2.1 Location of heap

Location of heap depends on several factors such as possible water content and its addition, temperature of the location, as well as elevation.

In arid environment, evaporation is the main threat to the open process which include heap and dump leach operations so that drippers are used to keep the loss of evaporable substances at its minimum point. However, using the dripping technology instead of sprinkling system causes longer leaching time in which leaching cycle is already at its highest.

At the dominance of low temperature, it is reported that recovery decreases especially in gold leaching (28).

The most desirable recovery can appear in warm and humid climate. However, maintaining water balance in humid climate can be challenging for the heap and dump leaching processes. Excess of water can negatively affect heap performance and solution management.

At elevated temperature, no problems regarding to the process is reported, but exceedingly elevated temperature leads to introducing drip irrigation system.

Elevation of the leaching place often results in lack of oxygen which is responsible for low processing time. Sulfuric ore of copper which needs oxygen to convert into leachable material has been severely hampered at the high altitude. However, gold leaching at high elevation shared similar leaching rate with the lower one.

2.2.2.2 Ore preparation

Although oxide minerals do require crushing and stacking stages, the processes do not possess significant danger to the environment. Stacking is often done in two ways, in particularly, truck dump and continuous conveyor.

Bio-oxidation is only viable solution for low grade secondary sulfide ore and slow process, therefore, pretreatment for refractory sulfide mineral is introduced in which comminution, agglomeration, and curing processes take place. As reported by (36), crushing or microwave pretreatments come to pass for greater surface area and proper size distribution, agglomeration and binding are intended for increasing permeability and creating pores of opening, and curing is dedicated to form highly soluble targeted metal sulphate where addition of chloride and nitrate, an increase of curing time and temperature has resulted in positive effect on copper recovery.

2.2.2.3 Heap height

When heap height is getting higher, permeability of lower zones is getting higher that influences flowrate of operating irrigation since bulk density increases and bed void ratio decreases affected by the over mass. The higher the heap, the lower is an extraction rate. However, there can be some advantages that comes with increasing height of heap, for instance, multi-stacking operation cost can be reduced.

When height of heap decreases, lixiviant and temperature distribution can be positively affected. Since volume per unit area is lower and heat is easily eliminated, temperature is efficaciously distributed within the heap.

During the leaching operation, heap height does not remain at constant due to a slump of heap. It leads to depressed bed voidage and permeability in which gas and liquid flow within the heap are affected (28).

2.2.2.4 *Leaching pad*

Crushed and ROM ore characteristics, seismic data for pad stability, water balance and solution management, pad, pond, and solution pipe containment and monitoring, heap height, potential extension, and reclamation and closure plans are all factors to be considered while designing the pad (37).

- On/Off pads – it is dedicated for low-grade precious metal ores in which permeability of thicker layers cannot be supported. The advantages of the on-off heap process are that water balance is easily manageable, especially designed for short leaching time and extremely small amount of gold in inventory, and sampling from the tailing during the pad unloading. The main disadvantages of such pad technology are well known for its high capital cost, double handling ore (loading and removing), and a limit to leach times.

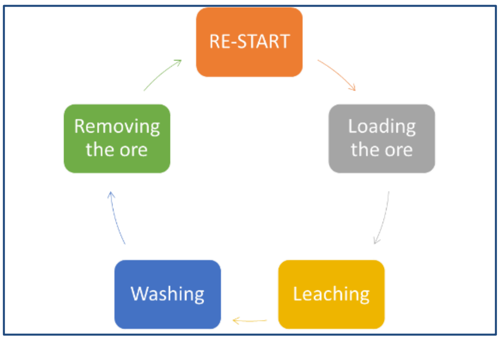

Figure 5. Dynamic heap simplified stages

The process is selected due to small amount of area for leaching pads, which is divided into arrangement of cells which provide between and outer spaces for solution collection systems. Since the pad is used repeatedly, vehicle traffic for un/loading the ore requires the leaching pad more durable; it often contains combination of layers of asphalt, rubberized layer, concrete or a traditional composite of clay and high-density polyethylene (HDPE) with protective gravel layers.

- Permanent pads – in which ore is stacked on a tabular ground surface and never removed. Based on number of lifts, the pad type can be divided into two groups as follows:
    - Single-lift heaps are designated for high grade, but not permeable ores and can grow through horizontal direction.
    - Multi-lift heaps are built due to permeability of ore bed in which lifts are stacked on top of previously leached lift. It gives a flexibility to grow both vertical and horizontal directions. The heap type provides an opportunity

to leach remained metal in the last heap while leaching new lift without any additional cost.

The optimal leaching pad is 2 to 3 percent downslope and 1% across slope, with clayey in situ material beneath the topsoil, adjacent supplies of clay or low-permeability soil for the pad foundation, and gravel for the protective/drainage layer (37). Permanent heaps are suitable when low initiation cost and less expensive operation are critically needed for the mine. However, long leaching time, large area requirement, and water balance issues negatively affects the process.

- Valley fill pads – are appropriate when necessary flat surface cannot be obtained near the mining area, hence, terrains are used for storing heap bed and pregnant leach solution by constructing dam at the base of the valley.

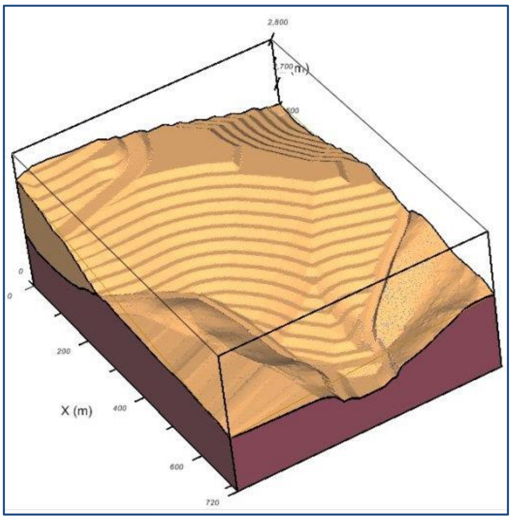

Figure 6. Valley fill heap model (38)

Other pad types are less suitable for truck and conveyer stacking systems for stacking the ore than valley fill pads which applies filling the valley from the top through the expansion stages. Complications in pad preparation and liner installation, greater installation costs, decreased flexibility with a single process pond, typically a necessity for staged expansions in solution treatment facilities, and rainfall dilution can occur while extending pads are some of the advantages of the pad (37).

2.2.2.4.1 Pipes of solution handling system

The stability of pipe depends on the adjacent soil deformity in addition to heap height, internal and external pressure. Deformation of soil negatively affects the pipe by increasing stress on the pipeline. Assumption of negligence of pipe collapse, the maximum pipe deflection equals to 40%.

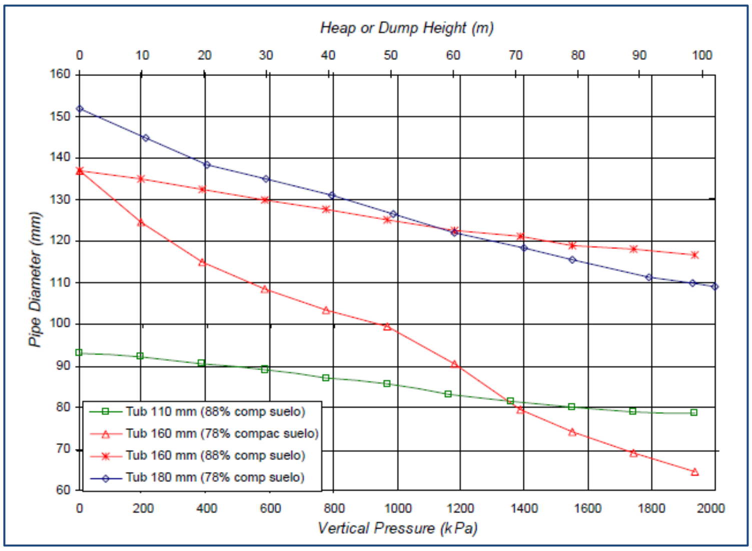

Figure 7. Load-deflection curve for double walled polyethylene pipe (39)

The researchers have studied (39) the survivability of the high-load installation pipe in which tubular diameter was varied from 110 mm to 180 mm under the condition of soil compaction in standard Proctor from 78% to 88%, 50^{0}C temperature, and up to two thousand kPa load. The result has shown 6% to 54% deformations in particular scenarios.

2.2.2.4.2 Liner construction

Generally, the liner system comes with two options as shown in Figure 8 distinguished by its composites. Single composite liner system consists of an overline layer, geomembrane liner, liner bedding soil, and prepared foundation besides double-composite liner system additionally contains leak detection layer and lower geomembrane layer (37).

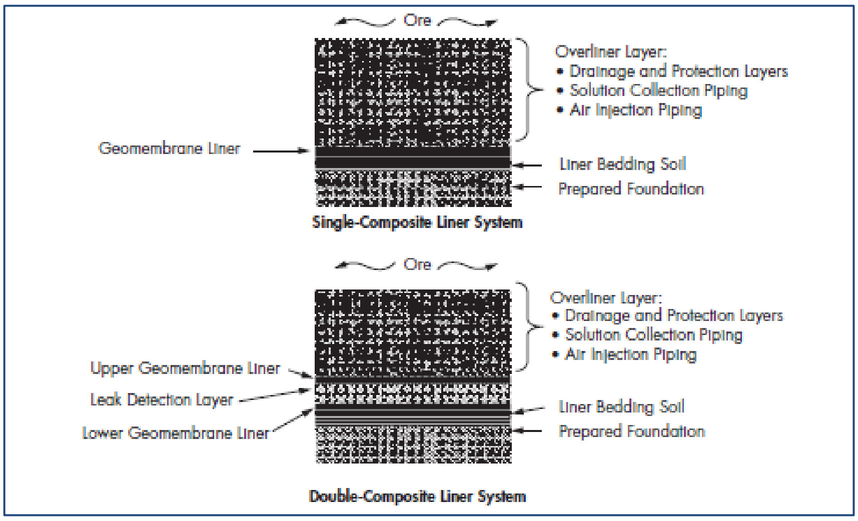

Figure 8. Liner construction structures (37)

Although double-composite liner system has higher cost than the single-composite liner system, the liner provides safety with the layers specially designed for leak to environment detection and prevention. Leakage of solutions to the environment could led to immense disaster by harming and disbalancing the surrounding ecological system.

2.2.2.4.3 Liner piles of the heap

Since heap leach process involves with intense base pressure and high moisture conditions, it is critical to consider the stability of piles. Heightening the heap and its lifts and increasing solution flow cycle to recover the metals while minimizing the metal-in-inventory (unrecovered metals in the bed) could harm the stability of the heap liners. Other sources of issues related to lowering the stability are static stabilities and liquefaction potential proposed by (39).

Typical liner is made of high-density polyethylene (HDPE), linear low-density polyethylene (LLDPE), and less commonly polyvinyl chloride (PVC). The ageing tests are made on those materials by exposing to 98% sulfuric acid for 120 days in which temperature equals 50^{0}C (39).

Material	Thickness	Tensile strength		Tensile elongation		Puncture	Tear	Hardness	Oxidative Induction Test
		Yield	Break	Yield	Break				
HDPE	1.5 mm	2/-4	-4/-4	-5/5	5/0	-3	-3/2	0	-64
LLDPE	1.5 mm	0/0	-7/-11	-10/9	-7/-12	1	-5/5	5	-73
PVC	0.75 mm	173/188	54/54	NA	-66/-76	130	107/112	31	Not Applicable

Table 5. Ageing test results for machine and transverse directions at 120 days (39)

In the tables, machine and transverse directions are given when two values are shown in one cell and the value represents the percentage change of the properties after exposure compared to the initial test value. Oxidative induction test is not conducted at PVC since the test is only applicable for polyethylene.

Immersion time (days)	Tensile strength at break	Elongation at break	Puncture	Tear	Seam shear elongation
30	31/27	-58/-74	129	119/122	-90
60	62/40	-71/-75	120	122/110	-94
120	54/54	-66/-76	130	107/112	-86

Table 6. Ageing test result of PVC (39)

Test on PVC was conducted several times from a month to 4 months where elongation decreases while increasing tensile strength indicates that plasticizer was lost, and the material becomes more brittle from flexible. From the data, PVC should be excluded from any liner layer which contacts with acid pre-curing operations.

2.2.2.5 *Modeling of heap*

Orr sufficiently described an application of modelling heap in enhanced heap leaching (40) in which they studied and modelled dependance of differentiation of application rates and heap designs on changes in flow paths and enhanced leaching recovery. The hypothetical heap designs included ore lifts that were crushed and stacked consistently, as well as run-of-mine lifts that were built by vehicles depositing blasted rock. Whereas application rates are differentiated as high application rate, medium application rate, and low application rate. Furthermore, effect of application rates on flow in portions of ideal heaps with altered saturated permeability.

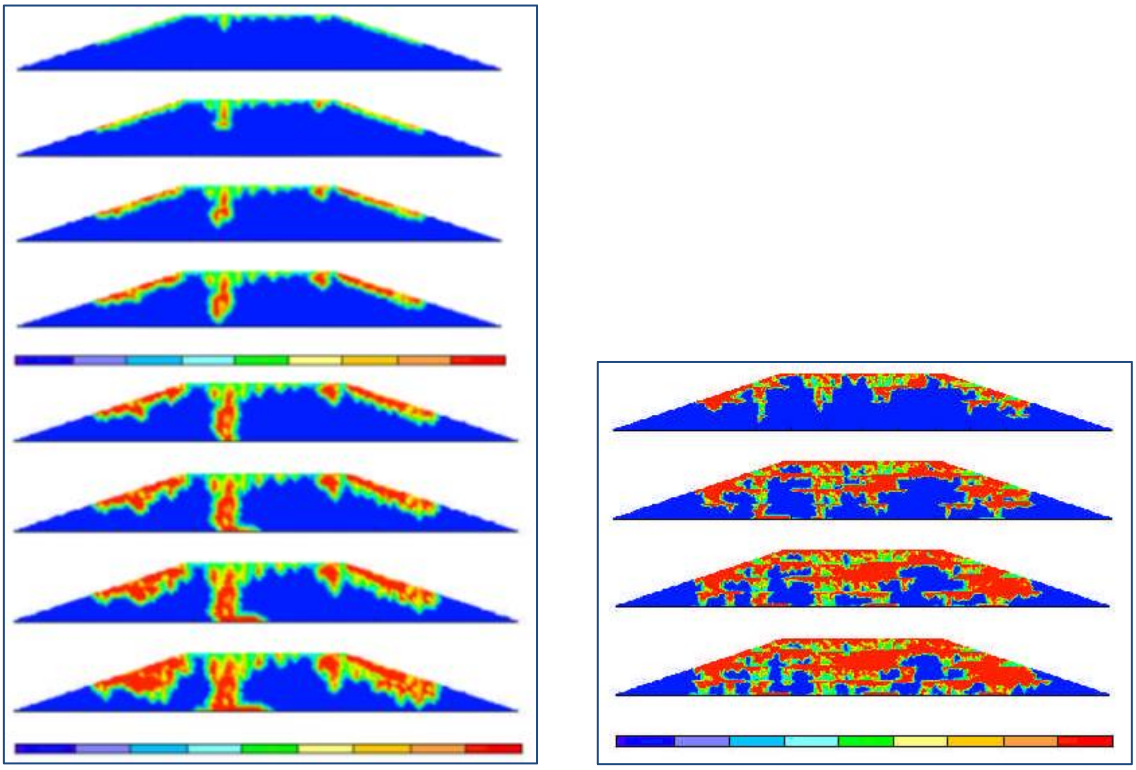

Figure 9. Modelling of flow in (a) the dump for 2, 4, 6, 8, 10, 12.5, 15, and 20 days, and the heap leaching for 2.5, 5, 7.5, and 10 days (40)

The simulation shown in the Figure 9 and other modelling could provide a clear view of probable flow patterns, transport pathways, and unleached zones with regards to variables of time, irrigation rate and distribution, as well as irrigator placement for both heap and dump leach mining. The modelling can be validated by field and/or laboratory tests, be calibrated in the specific mine locations which cover historical and current data of geophysical mapping including high resolution resistivity as well as hydrogeological and chemistry data of obtained from the running mine.

2.2.3 Closure of the leach mining

Kauppila et al. (41) proposed and implemented Mine Closure Wiki in which closure technologies and related research can be easily accessed with concise contents such as introduction, description, applications, performance, design requirements, and references.

The main potential hazardous constituent factors of the drainage water from tailing containments and spent heap and/or dumps are acidity, weak acid dissociable cyanide, iron precipitates, and dissolved heavy metals that may have impacts on groundwater, aquatic life, soils, sediments, as well as surface waters (42). The more mining site area, the more effect on the environment and surroundings. Acid mine drainage and the discharge of contaminants from mine leachates, for example, have had a substantial impact on water supplies. As a result, it is critical to safeguard the ecosystem, as well as the adjacent ground and surface waterways, from the consequences of mining. Furthermore, in areas where water resources are scarce, managing water usage is critical in order to lessen conflict in drinking water and agriculture. Water may be both a resource and a danger to miners and the general public, as seen by subsurface leaks or groundwater re-rise, both of which alter the geotechnical stability of mined land (43). Without any treatments toward the area which contains mined waste rocks and/or tailing storage facility, it still possesses threats to the ecosystem and human health.

Gangue chemistry

Due to their sheer size, sulfidic waste rock dumps and spoil heaps are the primary sources of acid mine drainage (AMD). The qualities of waste materials have a big impact on the composition and amount of AMD seepage fluids coming from sulfidic heaps. Complex weathering mechanisms cause AMD to form in trash piles. Different rates of various weathering processes inside the waste may result in temporal variations in drainage chemistry. Contributing three factors associated with composition of drainage waters are listed as follows (42):

- The hydrology of the waste pile: It includes hydraulic conductivity, transmissivity, porosity, pore water velocity, and recharge. Increase in the volume and pores caused by the mining process allows oxidants and water to flow. Several measures of minimizing hydraulic conductivity such as keeping dump under the water table within the saturated zone in which flow rates are comparably slow, settling dump materials which restricts the movement of particles, should be taken to prevent from acid generation. However, the hydrological properties are varied in place-to-place, hence, it should be considered for each specific location.

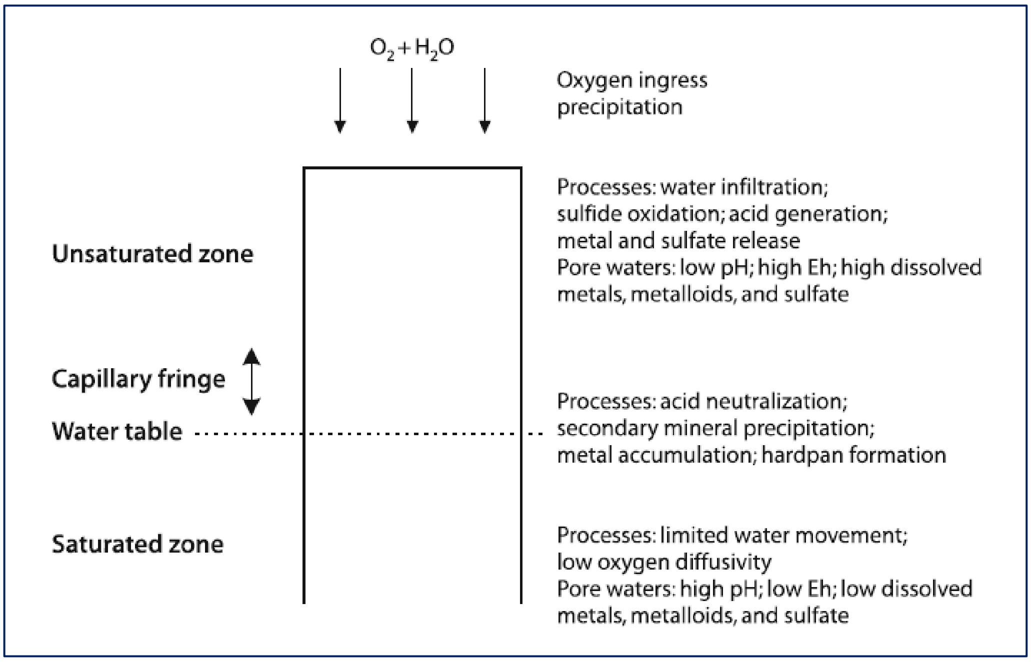

Figure 10. Unsaturated and saturated zones (42)

- The presence of different weathering zones within the pile: The zones are divided into outer unsaturated zone, unsaturated inner zone, and saturated lower zones where oxidation site distribution and chemical reactions distinguishes from each other.
- The rate of weathering reactions: Weathering processes occur in mine wastes with different rates. The difference in the rate of weathering depends on the soluble types, for instance, sulfates and carbonates quickly dissolve but with limited amount while silicates and sulfides weather slowly. When rinsing and flushing processes are conducted, the drainage chemistry differs with the rate of neutralizing agent dissolution.

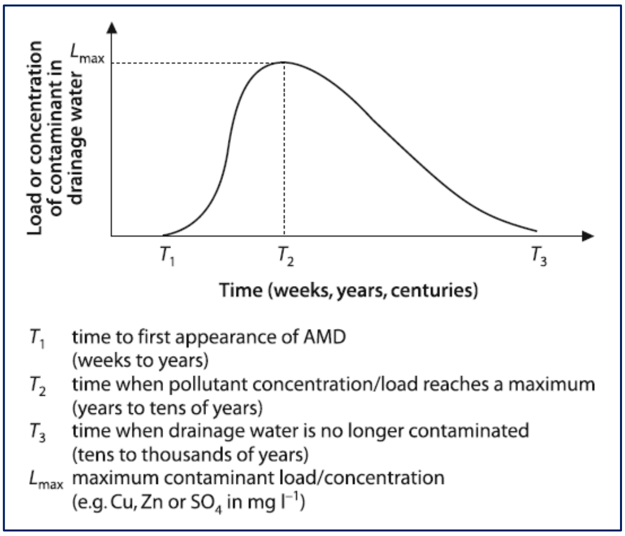

Figure 11. Concentration alteration versus time (42)

Treatment technologies used in closure

Edwards et al. (44) has successfully implemented an encapsulation for limiting mine drainage with two phases method in which drainage channels were constructed with geosynthetic clay liner in phase 1 and mine site was sealed with combination of geosynthetic clay liner and locally sourced low permeability clay. Abandoned mines were remediated in Portugal (45) by applying different methods confining and sealing the mine wastes with multilayer cover for radioactive waste, clay cover system, and high-density polyethylene and asphalt cover system in Figure 12, as well as mine water management in Figure 13.

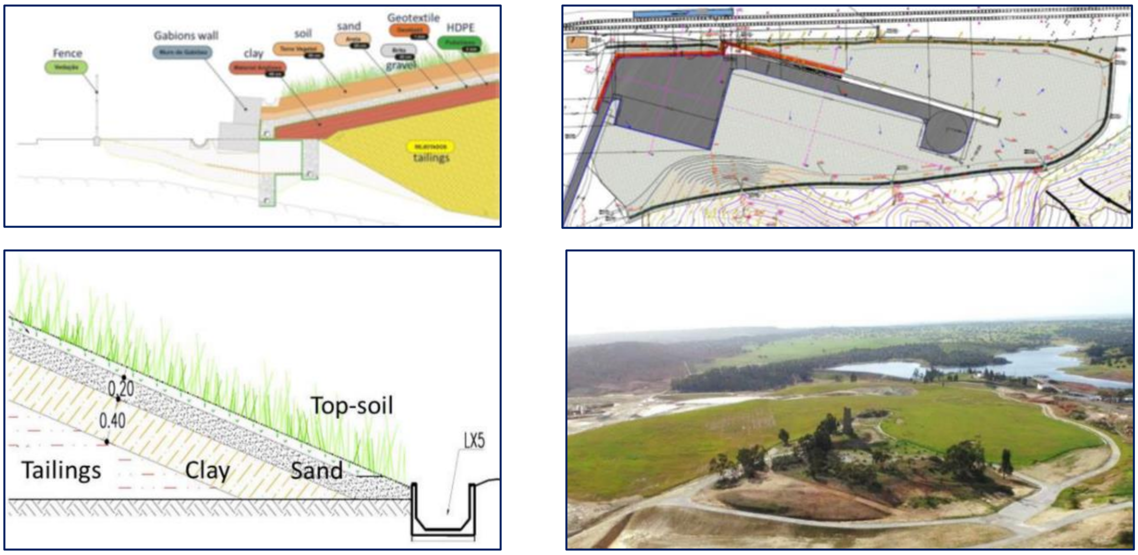

Figure 12. Cover systems [1] multilayer, [2] HDPE-asphalt, [3] clay liner, and [4] clay covered remediation (45)

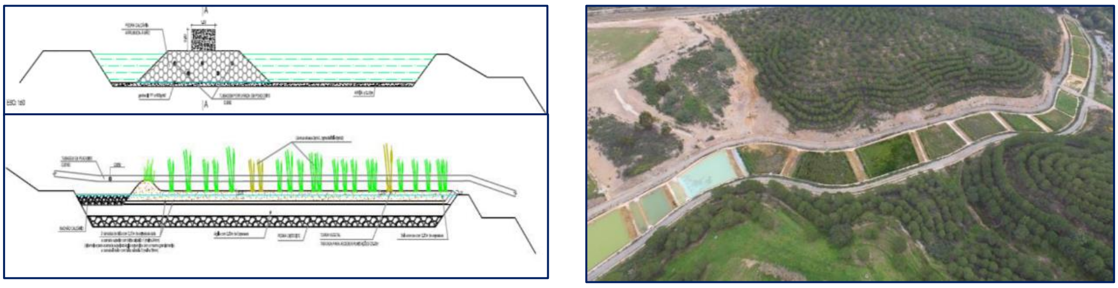

Figure 13. Passive treatment system progress and photo

Currently, monitoring by satellite supported system (46) was developed used in post mining verifications via utilizing remote sensing method where mining takes place in huge area. Simulation of 3D numerical model was developed (47) for monitoring the water table and saturated zone of the tailing storage facility.

2.3 Legal environment and standards of the mining in the country

2.3.1 Mongolian Laws related to Mining and Environment

In order to provide precise, concise, and relevant content of laws, the articles are carefully chosen, and some sub-articles are not provided in this third-level subsection. This section only sets the legal background with regards to mining and environment. The translation by Ministry of Justice and Home Affairs of Mongolia can be used for only research and study, and the parties of the government and the author is not responsible for any issue related to this informal translation.

2.3.1.1 Article 39. Environmental protection obligations of mining license-holders of MINERALS LAW OF MONGOLIA (48)

A mining license-holder shall have the following obligations with regard to environmental protection:

- an environmental impact assessment and an environmental management plan shall be prepared by a person before obtaining a mining license, and by the person who obtained a mining license through tender;
- the environmental impact assessment shall identify the possible adverse environmental impacts from the proposed mining operations regarding public and health, environmental and shall include preventive measures that avoid and minimize such adverse impacts;
- the environmental management plan shall contain measures to ensure that mining operations are conducted in the least damaging way to the environment. The plan shall also identify preventive measures to protect air and water, humans, animals, and plants from the adverse impacts of mining operations;
- an environmental management plan must include the following:
    - storage and control of toxic and potentially toxic substances and materials;
    - protection, utilization and conservation of surface and ground water;
    - construction of tailings dams and ensuring the mine area safety;
    - reclamation measures;
    - other measures as may be appropriate for the particular type of mining operation.

Mining license-holders shall record all instances of adverse environmental impact resulting from mining activity, prepare and send a copy of its annual report on the implementation of the environment management plan to the State central administrative agency in charge of environment, the Governor of relevant aimag, soum or district and the state professional inspection agency. The report shall contain the following:

- information on measures taken to protect the environment;
- new machinery and technology utilized;
- proposed amendments to the environmental impact assessment and environmental management plan with regard to possible adverse impacts on environment due to expansion of mining operations and enhancement of its production capacity.

The State central administrative agency in charge of the environment shall require the license-holder to provide amendments to the environmental management plan and environmental impact assessment if new circumstances arise which have adverse impacts on environment due to introduction of new equipment and technology during the valid license term.

2.3.1.2 ENVIRONMENTAL IMPACT ASSESSMENT LAW OF MONGOLIA (49)

The purpose of this law is to implement the Article 16.2 of the Constitutional Law of Mongolia, protect the environment, prevent the loss of the eco imbalance caused by the human activities, exploit the mineral resources with the minimal adverse impact on the environment, assess the environmental impact of the policies to be implemented within the region and industry, the development program, plan and the projects and make decisions and conclusions whether to implement them and arrange coordination between the stakeholders.

In the law, environmental impact assessment contains following evaluations:

- The strategic assessment of the environment
- The evaluation of the environmental status
- The assessment of cumulative impact
- The environmental impact assessment.

The strategic assessment shall be ensured by the line ministry that initiates and develops the policy, program, and plan.

The evaluation of the environmental status shall be conducted by the project implementer with the authorized professional organization.

The assessment of cumulative impact at certain locations shall involve the interposition of the central administrative body in charge of environmental affairs. When necessary, the Cabinet Member in charge of environmental affairs of the Mongolian Government may appoint a technical team to conduct the assessment.

The environmental impact assessment shall consist of following:

- The general assessment of the environmental impact – it is required to be conducted prior to implementation of the project, owning the land, or utilizing the land for the purposes of running husbandry, exploration and exploitation of oil and minerals. The conclusion of the assessment consists of decline or return of the project, as well as whether the detailed environmental impact assessment shall be conducted or not at certain conditions and term.
- The detailed assessment of the environmental impact – its purpose, direction, and scope and timeframe shall be clearly indicated by the conclusion of the general assessment of the environmental impact. The assessment shall be conducted by the authorized local organization, and the project implementer is responsible for the financing. The following issues shall be reflected within the detailed environmental impact assessment:
    - The typology of the environment of the project implementing area
    - The calculation and research findings of the potential and key adverse impacts, their intensity, and consequences
    - The recommendation of methodology to eliminate and minimize the potential and key adverse impact
    - The recommendation on the use of method and technology and utilization of the environmentally friendly plants and technology in order to minimize the adverse environmental impact caused by the project operation
    - The risk assessment upon the human health and environment caused by the project operation if it is required to conduct within the detailed environmental impact assessments
    - The close-up activity direction, rehabilitation purpose, scope, criteria and corresponding protective measures for the oil, mining, and radioactive minerals projects
    - The purpose, scope, and criteria of the environmental management plan
    - The proposal and meeting minutes of the local government, local assembly for the area where the project is going to be implemented
    - Other issues related to the historical and cultural findings on the project area and features of the project.

The **environmental management plan** shall be developed by the organization who conducted detailed environmental impact assessment in order to protect the environment of the project area, utilize appropriately, rehabilitate, ensure the compliance of the strategic assessment recommendation, minimize, prevent and eliminate the adverse impact that is determined by the detailed environmental impact assessment, control and determine the potential consequences upon the project implementing environment. It is the essential part of the detailed assessment. The plan shall include following:

- Environmental protection plan – it reflects the method of mitigating and eliminating the adverse impact, corresponding protective measures, the required time, and funding.
- Environmental monitoring program – it consists of monitoring and analyzing of the variation upon the environment that is caused by project operation, reporting the results, the methods of implementation, required funding, cost and timeframe.

2.3.1.3 ***MINING, PROCESSING AND CONCENTRATION PLANT RESTORATION AND CLOSURE REGULATION*** (50)

The purpose of this regulation is to implement Minerals Law of Mongolia and Environmental Impact Assessment Law of Mongolia by developing mining, processing, and concentration plant restoration and closure management plan, organizing a preparation of the closure and its implementation.

When any of following conditions occur, the project implementer is eligible to request for the complete closure of mining:

- The deposit reserve cannot be mined in plant scale, is determined as unprofitable by the feasibility study of the deposit
- The exhaustion of the reserve is verified with the governmental census

Closure management plant shall consist of the following:

- Project overview, closure purpose and objective
- Land use after the mining
- Physical stability of post closure operation
- Chemical stability of post closure operation
- Measures of dismantling, resettling, demolition, and securing of infrastructure, machineries, and construction
- Closure restoration plan for maintaining physical and chemical stability, residential health and safety, and environmental protection

- Detailed plan of activities towards mine workers who operate on the site before and after the closure
- Detailed plan of preparation and transition activities of the mine
- Risk assessment of post-closure mine, as well as detailed plan of prevention and taking down activities
- Detailed plan of post closure monitoring, maintenance, and concern
- Temporary or unexpected mine closure plan
- Total cost estimation

With the closure management plan, necessary documents stated in Table 7 must be appended to the plan by the regulation.

№	ITEM
1	The request
2	Copy of registration of company
3	Copy of the special license
4	The feasibility study (valid and updated)
5	The detailed environmental impact assessment
6	The environmental management plan
7	The mine plan
8	The water use contract
9	The land use contract
10	The cooperation contract with local government
11	The statement of tax office
12	The statement of judicial office
13	The evaluation of the environmental status
14	The figure of soil in the land
15	The figure of vegetation in the land
16	The contour map of the land surface
17	The figure of reclamation of the barren land
18	The contour map and explanation of the bottom, bench, surface, and access road scheme of the mine pit
19	Rock movement map
20	Vegetative soil distribution scheme
21	Waterpipe, drainage, protection channel, and road scheme
22	Reclamation plan calendar of workers
23	The detailed map of pits which requires demolition by explosives, backfilling, waterfilling, necessary additional support, or conserving
24	The map and cut of possible risky corruption boundary
25	The remaining reserves, the map and cut of the predicted reserve
26	The detailed map of technical reclamation land
27	The detailed map of biological renaturation land

Table 7. Required documents for closure management plan (50)

Before starting the reclamation for the closure, following environmental criteria must be fulfilled:

- There shall not be any dangerous conditions such as percolation to underground water source, land crack, or recession near to the plant, the mine, the city, and/or residential area
- Air, soil, water shall be prevented from any pollutants, and prevention measures shall be taken to keep water reserve not exhausted

Funding of the closure has to be sufficient enough for reclamation, closure, post closure monitoring, maintenance, and mine surveying. The law states the contents of closure cost as follows:

- Reduction and precaution of effect on environment, society, and health caused by the mining and processing plant, as well as technical and biological renaturation of barren land
- Safety operations regarding the mining site cost
- Administration and management cost for executing the mine closure
- Post closure monitoring-surveying, maintenance, and service cost

The above stated closure cost shall be raised by cumulation and saved in the closure fund. Furthermore, it is possible to by shift into temporary or sudden closure mine mode with an initiation of the project implementer in the consideration of following conditions:

- The operation condition is changed due to the complication of mining or hydrogeological reform
- The operating cost is not available to receive required funding
- The raw materials market price dropped
- The mine reserve found by the exploration is not valid anymore, or requires additional exploration
- The loss of environmental or ecological balance is occurred
- The influence condition which harms or risks the environment is created
- The force majeure is confronted

Particular information, mine closure database, shall be kept and provided to the public through environmental database and exploration, mine operation electronic database.

2.3.2 Mongolian Standards on Environmental Criteria of Pollutants

2.3.2.1 MNS 4586:1998 Water quality. General requirements (51)

MNS (Mongolian National Standard) 4586:1998 is dedicated for normalizing water quality to maintain the living condition for healthiness of people and balance ecosystem. However, the standard does not cover any special licensed water consumption, naturally mineralized water, and industrially influenced area.

Water quality represents the maximum value of chemical substances contained in a unit volume of water to meet environmental requirements and ecosystem balance. Chemical substance content must not exceed the permissible values stated in Table 8.

№	Indicator	Unit	Permissible value
1	Hydrogen ion index pH		6.5-8.5
2	Dissolved oxygen O_2*	mgO/l	>6 and >4
3	Biochemical oxygen demand BOD	mgO/l	3
4	Chemical oxygen demand - Permanganate COD	mgO/l	10
5	Ammonium nitrogen NH_4 - N	mgN/l	0.5
6	Nitrite-nitrogen	mgN/l	0.02
7	Nitrate-nitrogen NO_3 - N	mgN/l	9.0
8	Orthophosphate as phosporus PO_4 - P	mgP/l	0.1
9	Chloride Cl	mg/l	300
10	Fluorine F	mg/l	1.5
11	Sulphate SO_4	mg/l	100
12	Manganese Mn	mg/l	0.1
13	Nickel Ni	mg/l	0.01
14	Copper Cu	mg/l	0.01
15	Molybdenium Mo	mg/l	0.25
16	Cadmium Cd	mg/l	0.005
17	Cobalt Co	mg/l	0.01
18	Lead Pb	mg/l	0.01
19	Arsenic As	mg/l	0.01
20	Total chromium	mg/l	0.05
21	Chromium Cr^{6+}	mg/l	0.01
22	Zinc Zn	mg/l	0.01
23	Mercury Hg	ug/l	0.01
24	Mineral oil	mg/l	0.05
25	Phenol	mg/l	0.001
26	Surfactant	mg/l	0.1
27	Benzo(a)pyrene	ug/l	0.005

Explanation: * dissolved oxygen in groundwater must be higher than six mgO/l in warm condition and four mgO/l in ice covered condition.

Table 8. Permissible value of chemical substances in groundwater (51)

If any of chemical substance exceeds the values stated above, the water is considered as polluted, and acts should be taken to improve water quality. If any chemically hazardous substance is detected in groundwater, but not listed above, its permissible value will be determined as an extension.

2.3.2.2 MNS 5850:2019 Soil quality. Soil pollutants permissible value (54)

MNS (Mongolian National Standard) 5850:2019 is currently in persecution to identify soil quality in the country. The standard defines potentially harmful substances, pollutants, contaminants, and permissible values for soil.

The permissible values of soil pollutant are divided into following three groups:

- Precaution value – if a measured value of a pollutant contained in soil exceeds the precaution value, soil is considered as polluted. Precaution value shares a same meaning with permissible value. Precaution value is used in settled areas, grasslands, arable lands, and farming fields.
- Trigger value – if a measured value of a pollutant contained in soil exceeds the trigger value, soil starts to expose surrounding living organism and groundwater to danger. Trigger value is used as the permissible value for specially licensed industrial and mining site.
- Action value – if a measured value of a pollutant contained in soil exceeds the action value, extreme acts must be taken immediately, for instance, neutralization, removal, halting of site operation, and residence evacuation, etc.

Standardized permissible value of inorganic pollutants of soil is listed in Table 9 in which soil texture is classified into clay (clay content is more than 45%), loam (clay content is between 20 to 45%), and sand (clay content is less than 20%). The unit presented here is milligram-per-kilogram, it is also widely known as parts-per-million (ppm).

Item number	Indicator	Unit	Soil texture			Permissible value
			Clay	Loam	Sand	
1	Lead (Pb)	mg/kg	100	70	50	100
2	Cadmium (Cd)	mg/kg	3	1.5	1	3
3	Mercury (Hg)	mg/kg	2	1	0.5	2
4	Arsenic (As)	mg/kg	20	15	10	20
5	Chromium (Cr)	mg/kg	150	100	60	150
6	Valence-6 chromium (Cr^{+6})	mg/kg	4	3	2	4
7	Tin (Sn)	mg/kg	50	40	30	50
8	Strontium (Sr)	mg/kg	800	700	600	800
9	Vanadium (V)	mg/kg	150	130	100	150
10	Copper (Cu)	mg/kg	100	80	60	100
11	Nickel (Ni)	mg/kg	150	100	60	150
12	Cobalt (Co)	mg/kg	50	40	30	50
13	Zinc (Zn)	mg/kg	300	150	100	300
14	Molybdenum (Mo)	mg/kg	5	3	2	5
15	Selenium (Se)	mg/kg	10	8	6	10
16	Boron (B)	mg/kg	25	20	15	25
17	Fluorine (F)	mg/kg	200	150	100	200
18	Cyanide (CN^{-})	mg/kg	25	15	10	25

Table 9. Permissible values of inorganic pollutants in soil (54)

If soil is polluted with inorganic pollutants listed above, flora and groundwater will be contaminated with the pollutants which negatively affect to health of human, livestock, and fauna.

Item number	Indicator	Unit	Trigger value	Action value
1	Lead (Pb)	mg/kg	500	1200
2	Cadmium (Cd)	mg/kg	10	20
3	Mercury (Hg)	mg/kg	10	20
4	Arsenic (As)	mg/kg	50	100
5	Chromium (Cr)	mg/kg	400	1500
6	Valence-6 chromium (Cr^{+6})	mg/kg	20	50
7	Tin (Sn)	mg/kg	300	500
8	Strontium (Sr)	mg/kg	3000	6000
9	Vanadium (V)	mg/kg	600	1000
10	Copper (Cu)	mg/kg	500	1000
11	Nickel (Ni)	mg/kg	1000	1800
12	Cobalt (Co)	mg/kg	500	1000
13	Zinc (Zn)	mg/kg	600	1000
14	Molybdenum (Mo)	mg/kg	20	50
15	Selenium (Se)	mg/kg	50	100
16	Boron (B)	mg/kg	100	300
17	Fluorine (F)	mg/kg	800	1500
18	Cyanide (CN^{-})	mg/kg	50	100

Table 10. Trigger and action values of inorganic pollutants in soil (54)

3 Case study

3.1 Leaching practices in Mongolia

3.1.1 Altan Tsagaan Ovoo (ATO) gold mine (55)

The Altan Tsagaan Ovoo (ATO) gold mine is located in Tsagaan Ovoo soum, Dornod aimag, 660 km east from capital city Ulaanbaatar. The mine is currently owned by Steppe Gold LLC and produces gold since 2020. The project consists of four deposits, namely, ATO1, ATO2, ATO 4, and Mungu, which shares 37%, 8%, 38%, and 18% of the gold reserve of the project.

Resource Class	Tons (Mt)		Gold equivalent (g/t)	AuEq metal (M oz)
Measured	23.9	58%	1.84	1.4
Indicated	17.7	42%	1.44	0.8
Total	**41.6**		**1.67**	**2.2**

Table 11. Mineral resources by classes in ATO project (55)

As reported in Table 11, the ATO project resources are classified into measured and indicated parts that share 58% and 42% of the total resources, respectively. The gold equivalent (AuEq) represents economic value expressed in ounces of gold in the resources in which international metal prices are taken to the date.

Oxidation level	Cut-off (g/t)	Specific gravity (t/m³)	Tons (Mt)		AuEq (g/t)	AuEq metal (M oz)
Oxide	0.15	2.46	8	19%	1.26	0.3
Transition	0.4	2.59	10.3	25%	1.92	0.6
Fresh	0.4	2.64	23.3	56%	1.7	1.3
Total			**41.6**		**1.67**	**2.2**

Table 12. Mineral resources by oxidation level in ATO project

The mineral reserve is determined as proven and probable reserve of 2.6 million tons of 1.33 gram-per-ton gold and 13.83 gram-per-ton silver, which shares 62 percent and 32%, accordingly.

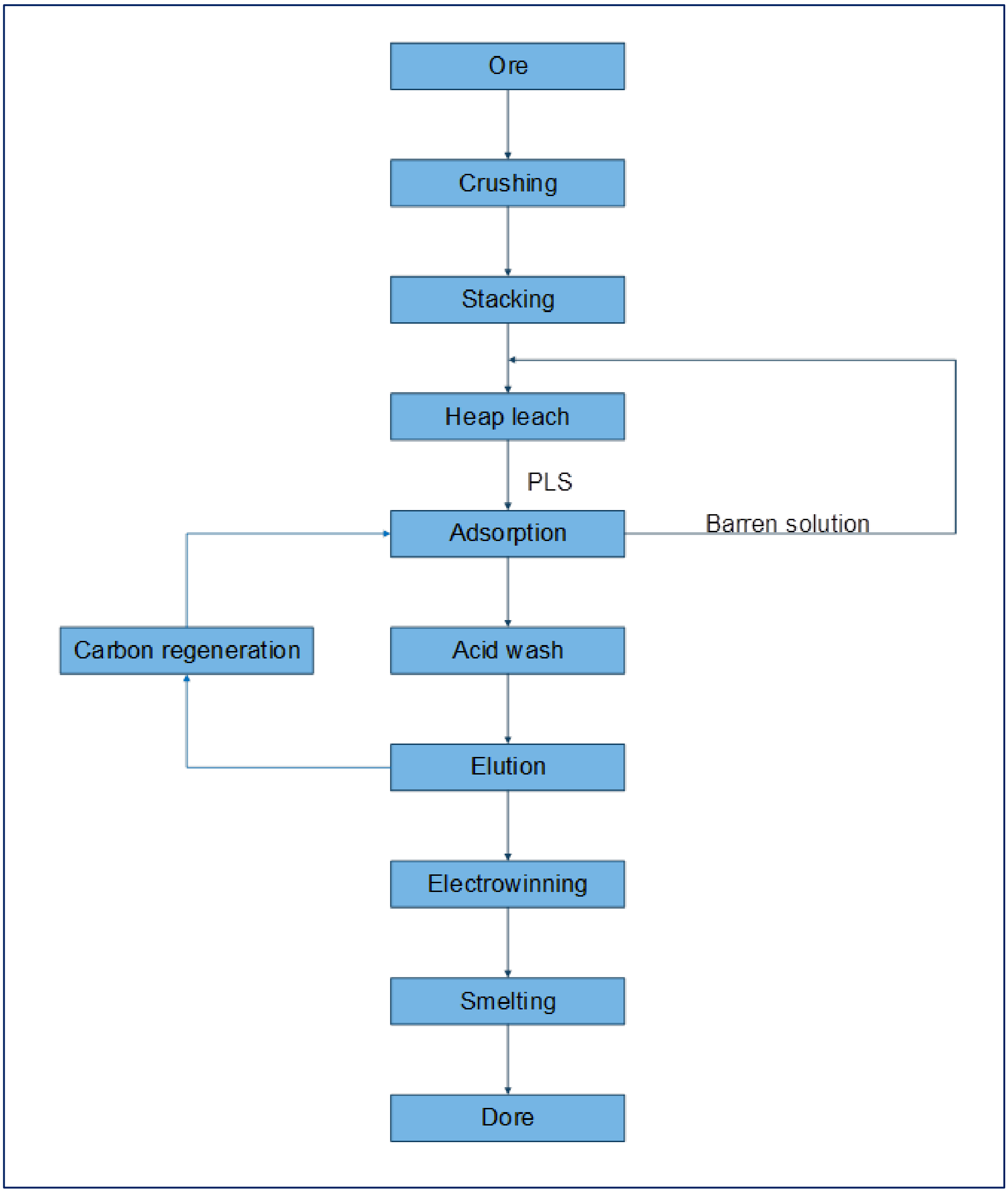

Figure 14. Processing flowsheet of ATO gold mine

The project is implemented in two stages, namely, Phase 1 and Phase 2. Current Phase 1 applies the heap leach facility whereas Phase 2 will utilize flotation circuit for recovering the metals in the newly found deposit. At the Phase 1, three-staged-crusher operates at a nominal 5860 tons-per-day for 275 days per year. It was designated to recover the ore contains 1.13 gram-per-ton of gold with recovery 70% and 9.25 gram-per-ton of silver with recovery of 40% in which crushed ore size of 10 mm. Undersize material of 3’000 tons stockpile leach feed from vibrating screen will be mixed with lime silo of two hundred tons for pH control.

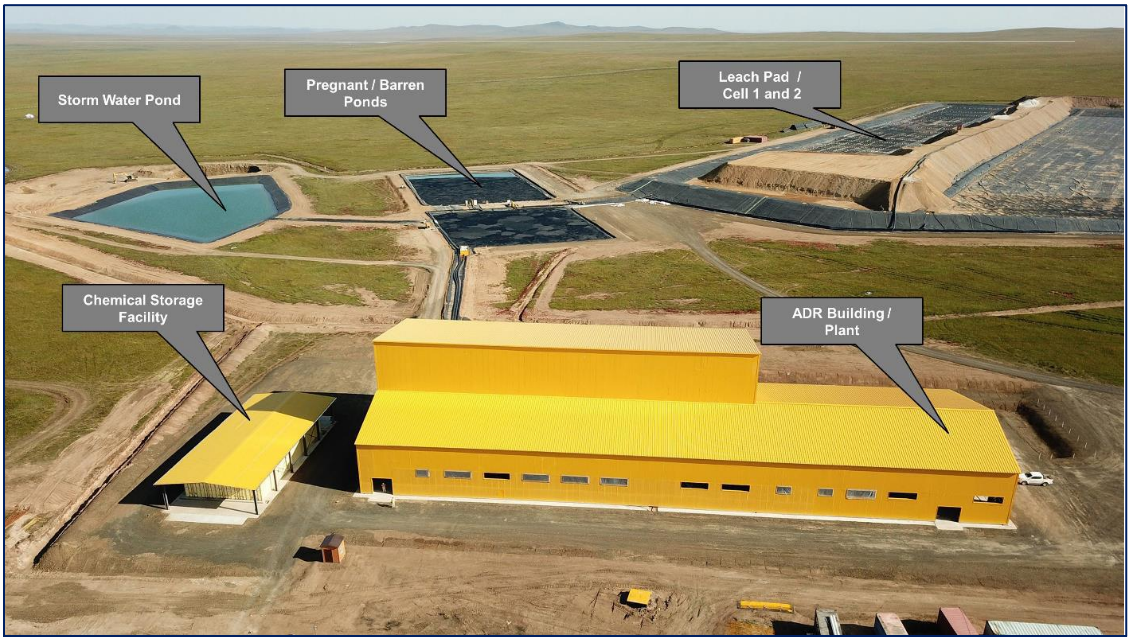

Figure 15. Process plant layout of ATO project

Heap is constructed with conventional three stage lift which has nominal height of 8 m in total 24 m and 5.6 Mt capacity. Leach pad is installed with a gently sloping head which provides free draining. Foundation of the pad was created with freeze stable soil, and waste rock and locally borrowed rock were used for drainage layer. Surface water flows are managed via permanent and temporary perimeter diversion canals and berms while considering access and haulage roads. The following steps listed in Table 13 was used to build the leach pad liner system.

Leach pad liner system
Drainage pipes installed to remove solution and minimize the hydraulic head directly over the geomembrane
Primary geomembrane liner, 1.5 mm LLDPE, bottom side agressively textured
Reinforced clay liner, 500 mm
Leak detection using horizontal wick drains to operate as large-scale lysimeters
Graded subgrade to provide a non-puncturing surface for the geosynthetic liner

Table 13. Liner system of ATO heap construction

To prevent any leakage through the pipelines, double walled pipes are used and an emergency pond for storm water collection was installed at the leaching site as shown in Figure 15 in addition to barren solution and pregnant leaching solution ponds. The entire system of Phase 1 uses sodium cyanide as lixiviant; therefore, the process is conducted under the International Cyanide Management Code. Cyanide solution addition to the barren pond is 0.2 kg/t of ore with the concentration of 0.1% cyanide in which lime is added with the rate of about 2.7 kg/t. Other reagents include sodium hydroxide for neutralizing acid wash and strip circuit contains hydrochloric acid, anti-scalant solutions for preventing membranes from scaling, and hydrated lime for controlling pH as mentioned above.

An independent environmental baseline assessment of the project was conducted in 2019; where quality of air, water resource, land and soil, biodiversity, cultural heritage/archaeology, population, and demography was studied by the certified independent organization. Furthermore, the general and detailed environmental impact assessment were made within the mine and environmental legislations with environmental and social management plan.

To prevent Acid Rock Drainage caused by the waste rock, repetitive testing method on site and laboratory scale will be conducted to provide sufficient data of waste rock and stockpiled ore for ARD model and implementation of environmental management plan. The ATO gold mine's actual as integrated mine closure plan will be established and implemented based on a set of principles organized into four main categories, in particular, physical stability, chemical stability, not long-term active care, and future sustainable usage.

3.1.2 Boroo Gold (Boroo) mine

The Boroo Gold mine is located in Bayangol soum, Selenge aimag, 120 km northwest from capital city Ulaanbaatar. During 2002-2003, project infrastructure such as the process plant, equipment workshop, and the first phase of the tailings facility were built, and the commercial production was delivered in March 2004.

Figure 16. Primary crusher and inside of processing plant of Boroo gold mine

The mine and processing plant is based on the Ikh Dashir gold deposit to recover gold with the Carbon-in-Leach (CIL) technology which consists of leaching gold with cyanide and recovering gold with activated carbon, and the gravitational concentrator. The processing plant has a capacity of treating three hundred tons-per-hour ore and the average grade of gold is equal to 2.5 to 3.5 gram-per-ton. The constituent of the ore is mostly oxidized, and the metal recovery equals to 80 to 94 percentage (56).

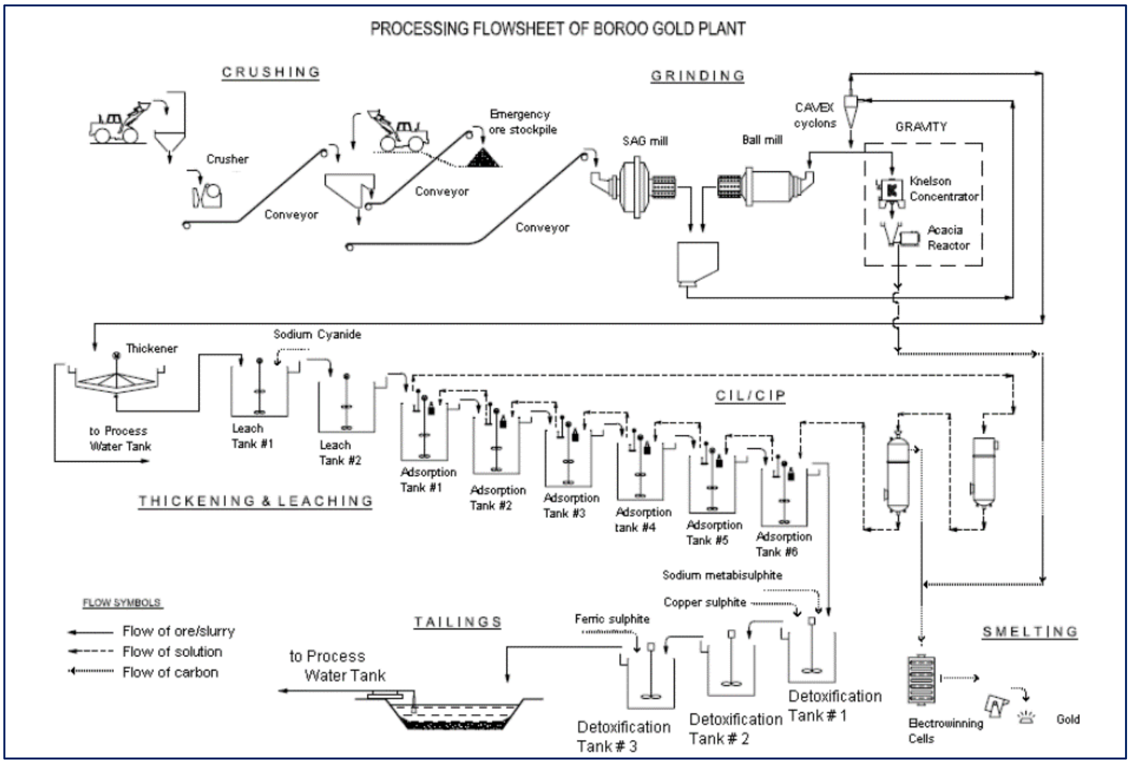

Figure 17. Processing flowsheet of Boroo gold mine (57)

The processing plant is divided into six main stages as follows:

1. **Ore crushing and storage**: ROM ore is conveyed with trucks and kept in the storage bin. The ore is conveyed into the primary jaw crusher, then semi autogenous (SAG) mill. Dust collector was installed beside the crushers which collects dust and dumps on the output of the primary crusher. Lime is added to SAG mill for controlling pH of the next stages.
2. **Grinding and gravitational separation**: SAG mill operates as a primary grinding stage and feeds hydro-cyclones of which overflow goes to the thickener whilst the underflow feeds secondary grinder - a ball mill and gravitational concentrator with a ratio of 80 to 20 percentage, respectively. The ball mill regrinds the material and the output is connected to the cyclones. In the gravitational concentrator, the Knelson concentrator separates comparatively big sized gold and feeds Acacia reactor which leaches gold in the cyanide solution. The outflow of the reactor is pumped to the electrolysis with the outflow of the desorption process. Gravitational concentration constitutes 0-70% percentage of the total gold and

average gold recovery is 50-55% (56). The tailings of Knelson and Acacia are mixed back with the outflow of the primary crusher.

3. **Gold leaching and adsorption**: In the leaching process, sodium cyanide is used for converting gold into gold ion with the concentration of 0.2 kg lixiviant per ton ore, and activated carbon is added for adsorption. The tailing of the adsorption tank is pumped to the detoxification tank.
4. **Desorption and electrolysis**: To recover gold from the carbon surface, the desorption process developed by Anglo American Research Laboratories (AARL) is used in which gold on carbon decreases from 1000-2000 ppm to 100 ppm. The process firstly washes with hydrochloric acid to get rid of calcium type impurities. Then, it is treated with cyanide and sodium hydroxide solution at elevated temperature and pressure of 120^0C and 150 kPa for 6 hours. Carbon is sent to regeneration furnace and activated up to 95%. Regenerated carbon is again fed to the CIL stage.

   Gold-rich cooled solution from the desorption is mixed with the outflow of the Acacia reactor, gold in the mixture is about 300-400 ppm, and pumped to the electrolysis tank in which gold ions selectively settle on the cathode made of steel wool. Gold-settled steel wool is processed at $600\text{-}800^0$C and smelted in the furnace for the production of gold dore.
5. **Detoxification**: The outflow of CIL stage is pumped to the detoxification in two-stage INCO Cyanide Destruction Process (58) is applied as shown below.

   Equation 4. Detoxification of cyanide process

   [1] $CN^- + SO_2 + O_2 \rightarrow OCN^- + H_2SO_4$

   [2] $OCN^- + H_2O \rightarrow CO_3 + NH_4^+$

   In the above process, an oxidation conversion of weak acid dissociable cyanide to cyanate contributes the first stage. The cyanate ion (OCN^-) is decomposed to carbonate ion and ammonium cation caused by its hydrolysis. Carbonate anion (CO_3^-) is precipitated as calcium carbonate, as well as some of ammonium cation (NH_4^+) will be released into the atmosphere as ammonia (NH_3) and rest will be changed into solid phase.

6. **Tailings**: Detoxified pulp streams down to the tailing storage facility located 5 km away under 150 m than the plant through HDPE pipe which has a diameter of 355 mm after checking concentration of cyanide and arsenic. Overflow of the tailing pond is back pumped to the plant as a processing water.

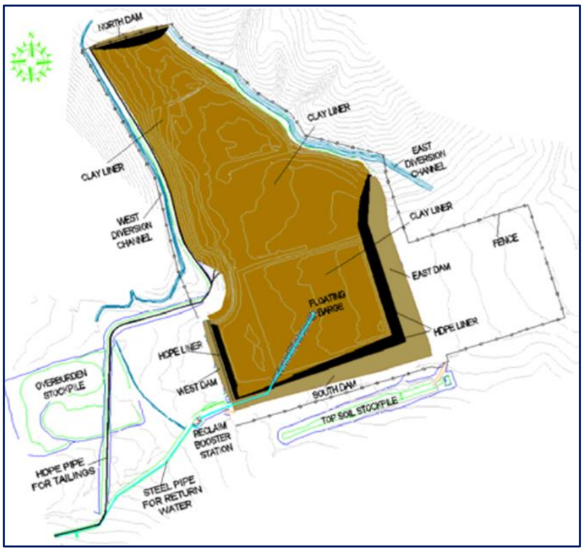

Figure 18. Tailing storage facility plan of Boroo gold mine (57)

The facility's containment dams are compacted earth fill structures with an interior granular drainage system as shown in Figure 16. Dams built using the "downstream construction" approach have several advantages over upstream or centerline methods. The downstream design is quite adaptable and operates similarly to water retention dams for a variety of site-specific design factors. Because the downstream design is suited for all types of tailings, is seismically resistant, and behaves similarly to water retention dams, it has a higher structural strength than the upstream or centerline methods. The key benefit is that because each raise is structurally independent of the tailings, the downstream design may have limitless heights. It was the first tailing facility in Mongolia; hence, the practice of this tailing pond was used for establishing standards and requirements related to the design to minimize the environmental impacts (57).

Figure 19. Comparison between ongoing and completed reclamation sites

The mining has been operating since 2003. project has completely finished in 2015, in particularly, open pit mining in September 2012, processing plant in December 2014, and heap leaching in December 2015. Although Boroo currently operates in the site, the information about re-operating of the processing plant is not sufficient to refer in this thesis research. The total land use of the project is approximately one thousand hectares in which the 4-section open pits, tailing storage facility, and other operational land contributes 90 ha, 230 ha, and 600 ha, respectively.

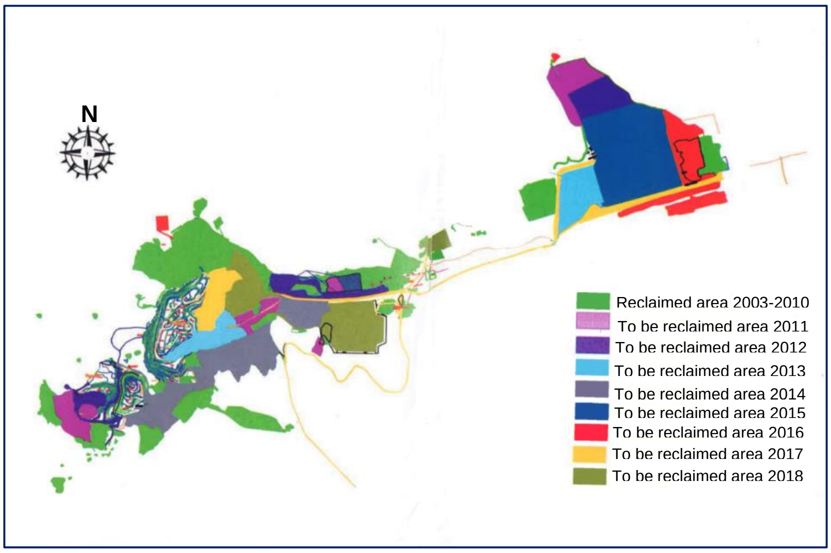

Figure 20. Closure reclamation area of Boroo gold mine by 2011 (59)

Reclamation of ecosystem is divided into technical reclamation and biological reclamation, but a reclamation plan, reforestation, site maintenance, and monitoring and tests have been conducted in the mining site of Boroo. The total reclaimed area was 306.2 hectares in 2013 (60), and remained area to be renatured area from 2018 to 2020 equals to 370.8 hectares in 2017 (61).

Reclaimed area (hectares)	
2003	10
2004	15
2005	16.5
2006	48.5
2007	21
2008	44.6
2009	52.1
2010	56.3
2011	55.2
2012	41
Total	360.2

Table 14. Reclaimed area by year (60)

In addition to restoring and monitoring the ecosystem, social and economic issues of workers and local residents have been considered in the closure management of the mine.

3.2 Leaching practices in the world

Firstly, the leach mines were selected randomly from the industry, and a domain list of selectable mines contains the following projects as in Table 15.

To make decision on choosing cases for the study, PESTLE analysis (political, economic, social, technological, legal, and environmental factors) is utilized in the process.

Political: It uses the index of political stability developed by the World Bank (62). The value represents that captures perceptions of the likelihood that the government will be destabilized or overthrown by unconstitutional or violent means, including politically motivated violence and terrorism in units of standard normal distribution ranging from the minimum value of -2.5 and the maximum value of 2.5.

Economic: The investment score developed by the World Bank (62) is used in this factor. The value stands for an ease of protecting investor and ranges from 0 to 100.

Social: Cultural and social norms developed by the World Bank (63) encourage or allow actions leading to new business methods or activities that can potentially increase personal wealth and income. The index ranges from 1 to 9.

Technological: The recovery technology used in the project is stated in the factor.

Legal: The regulatory environment score developed by the World Bank represents the ability of government to formulate and implement cohesive policies that promote the development. The score ranges from 0 to 100 (62).

Environmental: The environmental performance score developed by the World Bank (62) ranges from 0 to 100.

№	Project name	Country	Political	Economic	Social	Technological	Legal	Environmental
0		Mongolia	0.5	74		Heap, dump, VAT	69.5	32.2
1	Cerro del Gallo Au-Cu-Ag Project	Mexico	-0.7	25.9	3.11	Heap leach	54.9	52.6
2	Eagle Gold Project	Canada	1.0	73	3.61	Heap leach	92.7	71
3	Filo del Sol Cu-Au-Ag Project	Argentina	0.1	22.9	3.21	Heap leach	46.8	52.2
		Chile	0.4	36.4	3.05		69	55.3
4	Hycroft Gold Project	United States	0.6	73.5	4.05	Heap leach	93	71.2
5	Kipoi Copper Project	Congo, Dem. Rep.	-0.5			Heap leach		42
6	La Arena Gold Project	Peru	-0.8	29.5	3.3	Dump leach	68	44
7	Otjikoto Gold Project	Namibia	0.9	32.4	3.2	VAT leach	71.7	40.2
8	Sissingue Gold Project	Côte d'Ivoire	-1.1	28.2		VAT leach	61.6	25.8
9	Timok Gold Project	Serbia	-0.1	35.8	2.42	Heap leach	71.2	55.2

Table 15.Domain list of potential mines

After collecting individual data for the projects, selection of the cases takes place based on the scale as shown in Table 15. Listed values of political and economic parameters are prioritized by the relevance with the index of Mongolia. Since the social factor of Mongolia was not determined in the data, the social factor is neglected in the selection process. Technological factor affected the selection of potential projects listed in the table. Values of legal and environmental scores are also prioritized by the relevance. Therefore, Otjikoto gold project is selected for the case based on the minimum total variance of political, economic, legal, and environmental scores.

There are a few documents related to the closed mine which narrows the selection domain; hence, the author picked the mines for Case study #2 due to accessible documents and reports.

3.2.1 Case study #1: Otjikoto gold project (64)

The Otjikoto gold project is situated in the north-central part of the Republic of Namibia, northern 300 km from capital city Windhoek. It is indirectly owned by B2Gold and 10% interest is carried by EVI Mining Ltd. Otjikoto mine sources are divided into three groups, namely, Otjikoto open pit, Wolfshag open pit, and Wolfshag underground. Cut-off date of the Otjikoto open pit was in 2015, Wolfshag open pit was in 2018, and the underground construction is still in development stage.

Source	Indicated mineral			Inferred mineral		
	Tons (Mt)	Gold Grade (g/t Au)	Gold Contained Ounces (k Oz)	Tons (Mt)	Gold Grade (g/t Au)	Gold Contained Ounces (k Oz)
Otjikoto Open Pit	18.2	1.13	660	0.5	0.65	10
Wolfshag Open Pit	8.8	2.37	670	2.2	0.77	60
Wolfshag Underground	0.1	4.26	10	1.5	5.11	240
Total	**27.1**	**1.55**	**1350**	**4.2**	**2.27**	**310**

Table 16. Indicated and inferred mineral resources

In total, there are indicated 27.1 million tons of 1.55 gram-per-ton gold and inferred 4.2 million tons of 2.27 gram-per-ton gold. Wolfshag underground has higher grade of gold than the open pit mines.

Source	Tons (Mt)	Gold Grade (g/t Au)	Gold Contained Ounces (k Oz)
Otjikoto Open Pit	11.7	1.26	480
Wolfshag Open Pit	5.8	2.38	440
ROM Stockpile	2.3	0.86	60
Total	**19.8**	**1.54**	**980**

Table 17. Probable mineral reserves

The commercial production was announced in 2015. In 2021, the project comminution process accessed approximately 3.4 million tons of ore which has a grade of 1.68 g/t with recovery of 98% (65).

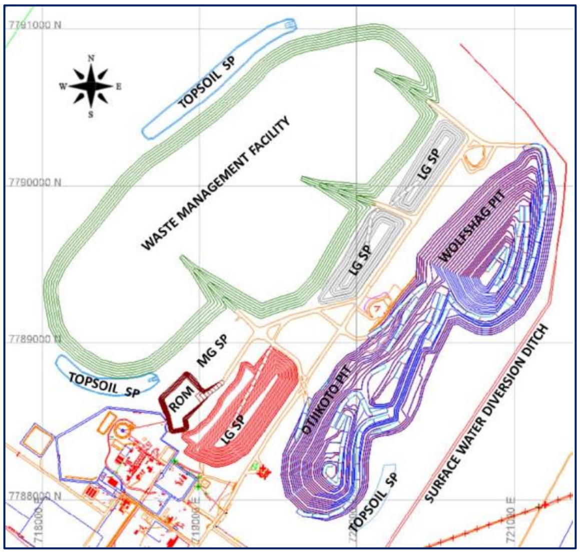

Figure 21. Mine layout plan of Otjikoto project

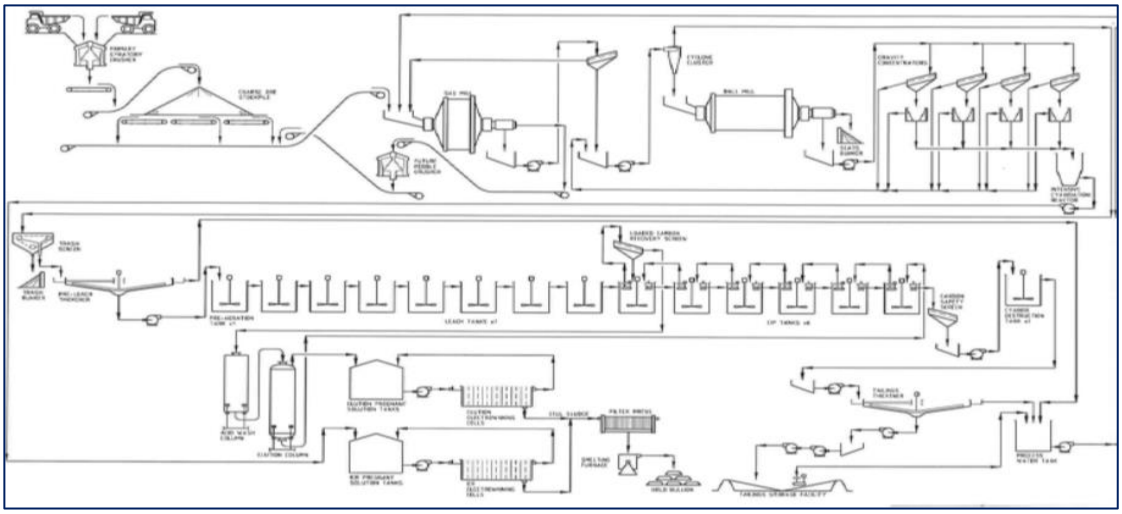

Figure 22. Processing flowsheet of Otjikoto gold mine

The gyratory crusher installed in the crushing circuit has a nominal throughput of 440 t/h, is fed by 100 t trucks, and has an 100% passing product size of 150 mm. SAG and ball mills then produce 80% passing product size of 75 µm with an annual mill throughput of 3 Mt/a. With Knelson concentrator and Acacia reactor, approximately 70.8% of gold is recovered with residence time of 48 hours. Carbon-in-Pulp (CIP) uses 0.59 kg of cyanide per ton of ore, and leach for 6 hours. In total 95.6% of the gold is recovered with a combination of the gravity concentration and tank leaching. The cyanide is decomposed with Air/SO_2 processed until the weak acid dissociable cyanide concentration is below than 10 ppm. Tailing, which flows to the tailing storage facility, has a 55-65% moisture. The reagents used in the process are sodium cyanide, caustic soda, hydrated lime, hydrochloric acid, sodium metabisulphite, copper sulphate, flocculant, elution de-scalant, and process water anti-scalant.

Waste storage facility is dedicated for the waste rock in which berm is designed with 15 m width and 10 m height. Tailing storage facility has a design of upstream structure in which liner was made of HDPE liner, and monitoring wells and drainage liner are checked regularly. The pond has a capacity of 36 Mt while considering the tailing deposition rate as 3.0 Mt annually. Moreover, the plant has a stormwater and evaporation ponds although the arid climate dominates the mining site which appears as low rainfall and extreme range of temperature from -5^{0}C to 39.7^{0}C and the annual evaporation rate is in excess of 2’500 mm.

By the end of 2018, the estimated cost for environmental reclamation and closure liabilities equals to 24.8 million USD. The mine closure framework was created to keep the baseline after the mine activity, such as air quality, visual landscape, groundwater and surface water, biodiversity, noise, and archaeological/cultural heritage.

3.2.2 Case study #2: Zortman and Landusky Mines

The Zortman and Landusky mines are located in Little Rocky Mountains in Montana, United States of America. The mines were operated as heap leach mine of gold from 1978 to 1998 and stopped the operation due to a suit of thirty-two million dollar clean up. The mine was found to be leaking acids, arsenic, lead, and cyanide involving an accident of 230’000 liters of cyanide spill during the operation. The company announced its bankruptcy and left the state without any proper reclamation. In 2000, the residents of Gros Ventre and Assiniboine Tribes sued the United States Bureau of Land Management (66) and the general reclamation with re-sloping, backfilling pit, renaturation, and water control took place from 2002 to 2005 (67).

Figure 23. Comparison between [1] before and [2] after reclamation of Landusky mine

In 2011, the yearly precipitation was 92.2 cm, and it was 44.4 cm more than an average of eleven years. The mines released acid mine drainage water in that year several times. Due to the flooding, neutralizing Zortman leach pad water costs $218’855, and additional 2011 cost over 2010 of neutralization of Landusky leach pad water was estimated as $39’189 (68).

Figure 24. Overflowing the capture pond of Zortman mine (68)

The reclamation process has been conducted in two primary components such as a technical reclamation of the mine and a capture and treatment of surface water, shallow ground water, and leach pad drainage (69). Several laboratory tests were conducted during the restoration period, in which paste pH and paste conductivity, the forward acid titration test, the net acid generation test, and leach extraction tests were performed, and results were introduced in land reclamation symposium (70). Case study in 2007 on analysis of acid mine drainage in Zortman and Landusky mines carefully examined the environmental effects and assessment, as well as risks, characteristics, reclamation, and prediction of AMD (71).

The water treatment plant – generator-powered Rotating Cylinder Treatment System™ would work at a capacity of ninety million liters per year with a cost of $0.0005 per liter. The system was installed at the place in 2008 and the result of treated effluent maintains the standards by that time (67). The treatment plan construction was completed in 2011, and the Bureau of Land Management supports the power cost of the system with $300’000 annually along with the wind turbine (72).

4 Conclusion and Recommendation

4.1 Conclusion

Copper is a metal that has numerous applications in our surroundings and industrial sector due to its physical and chemical properties whereas potentially pertinent applications of gold are extended with forthcoming and outstanding nanotechnology where gold nanoparticles play role in biological sciences, chemical platforms, and materials science.

Absence of high-grade deposits results in developing technologies which recover newly found or old stockpiled low grade, complex ores. Heap and dump leaching processes are designated for the low-grade ore since capital cost is relatively lower than other percolation leaching processes. However, the technologies of leaching huge sized heaps or dumps may bring threatens to the surrounding ecosystem. In order to provide an opportunity to evaluate the condition of the leach mine technologies without any bias, it is necessary to educate public with both strengths and weaknesses, as well as developing state of art technologies.

The thesis focuses on reviewing the heap and dump leaching technologies without disregarding the environmental impacts and concerns. The main source of environmental danger comes from any leakage or spillage of process fluids and pollutants contained in them. Therefore, several areas including flows, reagents, chemical reactions, and leaching pads are studied in advance. To set baseline of pollutant concentrations and mine-environment activities, relevant standards and laws have been introduced in this paper.

The dump leaching technology is less desirable than heap leach due to its long cycle of recovery, slow reaction kinetics, non-pad feature allowance of direct contact to the soil in some cases, and poor distribution of the lixiviant in the ore bed. The longer the exposure time to the environment, the greater chance of losing control of the possessed danger.

Percolation leaching process development in Mongolia has been being established and advanced with mining and environmental laws since early 2000s. The latest and the first Mongolian leach mining companies, Altan Tsagaan Ovoo gold mine and Boroo Gold mine were selected in studying leach practices in Mongolia. Boroo Gold project has been successfully conducting continuous reclamation of the mining site.

Case studies are carefully chosen in prior of similar mine operation and closed mine accident. It was clarified from the studies that mine closure should be planned in advance of the operation, closure fund must be guaranteed, and the post closure risks have to be considered.

4.2 Recommendation

The thesis work was designed to review research papers and study leach mining practices in comparatively descriptive and general scale. Therefore, quantitative analysis on comparison between technologies and mines is highly recommended for the further study.

The computational technology has been significantly developed in recent years besides mining methods. Calibrating of the modeling and simulation (e.g., computational fluid dynamics) with regards to the operating mine could bring huge opportunity to researchers and students apart from mining companies especially because the parameters and features are place-specific from mine to mine.

5 References

1. J.R. Davis, editor. Copper and copper alloys. ASM International; 2001.
2. Wang S. Copper leaching from chalcopyrite concentrates. JOM. 2005 Jul;57(7):48–51.
3. U.S. Geological Survey. Mineral Commodity Summaries 2022: U.S. Geological Survey. 2022.
4. U.S. Geological Survey. Mineral Commodity Summaries 2013: U.S. Geological Survey. 2013.
5. U.S. Geological Survey. Mineral Commodity Summaries 2014: U.S. Geological Survey. 2014.
6. U.S. Geological Survey. Mineral Commodity Summaries 2015: U.S. Geological Survey. 2015.
7. U.S. Geological Survey. Mineral Commodity Summaries 2016: U.S. Geological Survey. 2016.
8. U.S. Geological Survey. Mineral Commodity Summaries 2017: U.S. Geological Survey. 2017.
9. U.S. Geological Survey. Mineral Commodity Summaries 2018: U.S. Geological Survey. 2018.
10. U.S. Geological Survey. Mineral Commodity Summaries 2019: U.S. Geological Survey. 2019.
11. U.S. Geological Survey. Mineral Commodity Summaries 2020: U.S. Geological Survey. 2020.
12. U.S. Geological Survey. Mineral Commodity Summaries 2021: U.S. Geological Survey. 2021.
13. Corti CW, Holliday RJ, Thompson DT. Developing new industrial applications for gold: Gold nanotechnology. Gold Bulletin. 2002 Dec;35(4):111–7.
14. Zhou J, Gu Y. Geometallurgical Characterization and Automated Mineralogy of Gold Ores. In: Gold Ore Processing. Elsevier; 2016. p. 95–111.
15. Adams MD. Overview of the Gold Mining Industry and Major Gold Deposits. In: Gold Ore Processing. Elsevier; 2016. p. 25–30.

16. Fraser KS, Walton RH, Wells JA. Processing of refractory gold ores. Minerals Engineering. 1991 Jan;4(7–11):1029–41.

17. Adams MD. Gold ore processing: project development and operations. 2016.

18. George MW. Minerals Yearbook: Gold 2017. AdVANCE RElEASE. 2017.

19. Hartman HL, Mutmansky JM. Mining and Its Consequences. In: Introductory Mining Engineering. 2nd ed. John Wiley & Sons, Inc.; 2002. p. 25–46.

20. Spitz K, Trudinger J. Minerals, Wealth and Progress. In: Mining and the Environment from Ore to Metal. CRC Press; 2009. p. 2–67.

21. Dreisinger D. Copper leaching from primary sulfides: Options for biological and chemical extraction of copper. Hydrometallurgy. 2006 Sep 1;83(1–4):10–20.

22. Shafiee S, Topal E. An overview of global gold market and gold price forecasting. Resources Policy. 2010 Sep 1;35(3):178–89.

23. ALTANSUKH B, BURMAA G, NYAMDELGER S, ARIUNBOLOR N, SHIBAYAMA A, HAGA K. Gold Recovery from its Flotation Concentrate using Acidic Thiourea Leaching and Organosilicon Polymer. International Journal of the Society of Materials Engineering for Resources. 2014;20(1):29–34.

24. Udupa AR, Kawatra SK, Prasad MS. Developments in Gold Leaching: A Literature Survey. http://dx.doi.org/101080/08827509008952669 [Internet]. 2007 [cited 2022 Apr 25];7(2):115–35. Available from: https://www.tandfonline.com/doi/abs/10.1080/08827509008952669

25. Deschênes G. Advances in the Cyanidation of Gold. Gold Ore Processing. 2016 Jan 1;429–45.

26. Lee J. The art of heap leaching-The fundamentals." Percolation Leaching: The status globally and in Southern Africa. 2011.

27. Kappes DW. Precious metal heap leach design and practice. In: Mineral Processing Plant Design, Practice, and Control. 2002. p. 1606–30.

28. Ghorbani Y, Franzidis JP, Petersen J. Heap Leaching Technology—Current State, Innovations, and Future Directions: A Review. http://dx.doi.org/101080/0882750820151115990 [Internet]. 2016 Mar 3 [cited 2022 Apr 25];37(2):73–119. Available from: https://www.tandfonline.com/doi/abs/10.1080/08827508.2015.1115990

29. Petersen J. Heap leaching as a key technology for recovery of values from low-grade ores – A brief overview. Hydrometallurgy. 2016 Oct 1;165:206–12.

30. Manning TJ, Kappes DW. Heap Leaching of Gold and Silver Ores. Gold Ore Processing. 2016 Jan 1;413–28.

31. Kuhn MC, Alley RD. Copper Hydrometallurgy. In: Dunne RC, Young CA, Kawatra SK, editors. SME Mineral Processing and Extractive Metallurgy Handbook. Society for Mining, Metallurgy & Exploration; 2019. p. 1643–53.

32. Robertson SW, van Staden PJ, Cherkaev A, Petersen J. Properties governing the flow of solution through crushed ore for heap leaching. Hydrometallurgy. 2022 Feb 1;208:105811.

33. Maghsoudy S, Bakhtiari O, Maghsoudy S. Tortuosity prediction and investigation of fluid flow behavior using pore flow approach in heap leaching. Hydrometallurgy [Internet]. 2022 May 1 [cited 2022 May 6];211:105868. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0304386X22000536

34. Clotilde Apua M, Madiba MS. Leaching kinetics and predictive models for elements extraction from copper oxide ore in sulphuric acid. J Taiwan Inst Chem Eng. 2021 Apr 1;121:313–20.

35. Petersen J, Dixon DG. Principles, Mechanisms And Dynamics Of Chalcocite Heap Bioleaching. In: Microbial Processing of Metal Sulfides. Dordrecht: Springer Netherlands; p. 193–218.

36. Neira A, Pizarro D, Quezada V, Velásquez-Yévenes L. Pretreatment of Copper Sulphide Ores Prior to Heap Leaching: A Review. Metals 2021, Vol 11, Page 1067 [Internet]. 2021 Jul 2 [cited 2022 May 8];11(7):1067. Available from: https://www.mdpi.com/2075-4701/11/7/1067/htm

37. Pyper R, Seal T, Uhrie JL, Miller GC. Dump and Heap Leaching. In: Dunne RC, Kawatra K, Young CA, editors. SME Mineral Processing and Extractive Metallurgy Handbook. Society for Mining, Metallurgy & Exploration; 2019. p. 1207–24.

38. Reyes A, Garma P, Parra D. 3-D slope stability analysis of heap leach pads using the limit equilibrium method. 2014.

39. Thiel R, Smith ME. State of the practice review of heap leach pad design issues. Geotextiles and Geomembranes. 2004 Dec;22(6):555–68.

40. Orr S, Vesselinov V. Enhanced Heap Leaching: II. Applications. Mining Eng. 2002;54(10):49–55.

41. Kauppila PM, Kauppila T, Turunen K, Pasanen A, Wahlström M, Punkkinen H, et al. Mine Closure Wiki – Databank for Mine Closure. In: Drebenstedt C, Paul M,

editors. Mining Meets Water - Conflicts and Solutions [Internet]. 2016. p. 538–45. Available from: http://mineclosure.gtk.fi.

42. Lottermoser B. Mine Wastes. 3rd ed. Berlin, Heidelberg: Springer Berlin Heidelberg; 2010.

43. Drebenstedt C, Paul M, editors. Mining Meets Water - Conflicts and Solutions. In Leipzig: Technische Universität Bergakademie Freiberg; 2016.

44. Edwards P, Williams T, Stanley P. Surface water management and encapsulation of mine waste to reduce water pollution from Frongoch Mine, Mid Wales. In: Drebenstedt C, Paul M, editors. Mining Meets Water - Conflicts and Solutions. 2016. p. 546–53.

45. Carvalho E, Diamantino C, Pinto R. Environmental Remediation of Abandoned Mines in Portugal – Balance of 15 Years of Activity and New Perspectives. In: Drebenstedt C, Paul M, editors. Mining Meets Water - Conflicts and Solutions. 2016. p. 554–61.

46. Goerke-Mallet P, Melchers C, Müterthies A. Innovative monitoring measures in the phase of post-mining. In: Drebenstedt C, Paul M, editors. Mining Meets Water - Conflicts and Solutions [Internet]. 2016. p. 570–6. Available from: www.gmes4mining.de

47. Ethier MP, Bussière B, Aubertin M, Broda S. A 3D numerical model to assess the performance of the reclamation measures for an abandoned mine site. In: Drebenstedt C, Paul M, editors. Mine Meets Water - Conflicts and Solutions. 2016. p. 660–7.

48. MINERALS LAW OF MONGOLIA. Mongolia; Jul 8, 2006.

49. ENVIRONMENTAL IMPACT ASSESSMENT LAW OF MONGOLIA. May 17, 2012.

50. MINING, PROCESSING AND CONCENTRATION PLANT CLOSURE REGULATION. A/181, A458 Mongolia; Aug 28, 2019.

51. Mongolian Agency for Standardization and Metrology. Water Quality. General requirements. MNS 4586:1998, 1998.

52. Mongolian Agency for Standardization and Metrology. Environment. Health protection. Safety. Drinking water. Hygienically requirements, assessment of the quality and safety. MNS 0900:2018, 2018.

53. Mongolian Agency for Standardization and Metrology. Environment. Water quality. Effluent water. General requirements. MNS 4943:2015, 2015.

54. Mongolian Agency for Standardization and Metrology. Soil Quality. Soil pollutants permissible value. MNS 5850:2019, 2019.

55. Rankin RA. Altan Tsagaan Ovoo Project (ATO): 2021 Mineral Resources Technical Report. 2021 Mar.

56. Orgodol T. Gold Ore Processing Industrial Technologies of Boroo. In: Tsedendorj S, editor. Engineering Handbook. 2010. p. 565–74.

57. Dashjamts D, Erdenechimeg D. Environmentally Safe tailings storage facility of Boroo gold mine, Mongolia. In: 2008 Third International Forum on Strategic Technologies. IEEE; 2008. p. 623–8.

58. Mudder TI, Michael M, Botz PE, Smith A. The chemistry and treatment of cyanidation wastes [Internet]. 2nd ed. 1991 [cited 2022 May 15]. 327–333 p. Available from: http://dana6.free.fr/2%20SO2-Air%20cyanide%20oxydation.pdf

59. Boroo Gold LLC. Reference Book of Fauna and Flora of Boroo Gold Mine Reclamation. Vol. 1. Ulaanbaatar; 2011.

60. Boroo Gold LLC. Reference Book of Fauna and Flora of Boroo Gold Mine Reclamation. Vol. 2. Ulaanbaatar; 2013.

61. Boroo Gold LLC. Reclamation of Boroo Gold Mine (2013-2016). Ulaanbaatar; 2017.

62. The World Bank. Global Innovation Index. 2020.

63. The World Bank. Global Entrepreneurship Monitor National Expert Survey. 2020.

64. Technical Report for the Otjikoto Gold Mine. 2018.

65. B2Gold - A Low-Cost International Senior Gold Producer | Otjikoto Mine – Namibia [Internet]. [cited 2022 May 16]. Available from: https://www.b2gold.com/projects/producing/otjikoto/

66. Zortman-Landusky Gold Mine, Montana, USA | EJAtlas [Internet]. [cited 2022 May 16]. Available from: https://ejatlas.org/print/gold-mining-in-montana

67. Williams RD, Gabelman J, Shaw S, Jepson W, Gammons C, Eagle JK. ZORTMAN-LANDUSKY: CHALLENGES IN A DECADE OF CLOSURE. Journal American Society of Mining and Reclamation. 2009 Jun 30;2009(1):1583–95.

68. McCullough W, Jepson W, Maehl B. Zortman: Dealing with Extreme Weather Events. 2012.

69. Mitchell LD. Zortman & Landusky Mines HJR 43 Water Quality Impacts. 2004;

70. Shaw S, MacG Robertson A, Maehl W. 2000 Billings Land Reclamation Symposium MATERIAL CHARACTERIZATION AND PRIORITIZATION OF REMEDIATION MEASURES AT THE ZORTMAN/LANDUSKY MINE SITES.

71. Moran K. A critical analysis of acid mine drainage prediction within the environmental impact assessment process: A case study of the Zortman and Landusky mines. UNIVERSITY OF CALGARY; 2007.

72. Bureau of Land Management. ZORTMAN & LANDUSKY GOLD MINES [Internet]. [cited 2022 May 16]. Available from: https://www.abandonedmines.gov/success-story/zortman-landusky-gold-mines