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INSTITUTE FOR SUSTAINABLE WASTE MANAGEMENT AND TECHNOLOGY
University of Leoben
Franz-Josef-Straße 18
iae.unileoben.ac.at
A-8700 Leoben
accredited Laboratory according to ISO 17025

Master Thesis

Cyanide Leaching at the Kori Kollo Gold Mine, Oruro, Bolivia:

Comparing the Environmental Performance to European Standards of Gold Extraction

Submitted to the

Institute for Sustainable Waste Management and Technology (IAE) – University of Leoben

Presented by:
Thomas Reichard
9835021

Supervisors:
O.Univ.Prof.Dipl.-Ing.Dr. Karl E. Lorber
M.Sc.Ing. Jaime A. Rocha Valenzuela
Dipl.-Ing.Dr.nat.tech. Günter Tiess
Dipl.-Ing.Dr.mont. Stefan Konetschnik

Leoben, November 14, 2010

EIDESSTATTLICHE ERKLÄRUNG

Ich erkläre an Eides statt, dass ich diese Arbeit selbständig verfasst, andere als die angegebenen Quellen und Hilfsmittel nicht benutzt und mich auch sonst keiner unerlaubten Hilfsmittel bedient habe.

Thomas Reichard

AFFIDAVIT

I declare in lieu of oath, that I wrote this Thesis and performed the associated research myself, using only literature cited in this volume.

Thomas Reichard

Institute for Sustainable Waste Management and Technology

Universidad Mayor de San Andres

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There is no debt, which is more urgent to settle, than to express one's gratitude.

Marcus Tullius Cicero (106-43 BC.)

I would like to express my heartfelt gratitude towards everyone who supported me in completing this Master Thesis.

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Kurzfassung

Zyanidlaugung in der Kori Kollo Goldmine, Oruro, Bolivien:
Ein Vergleich der Umweltleistung mit Europäischen Standards der Goldgewinnung

Die Laugung von Golderzen mittels Zyanid ist die weltweit am meisten verbreitete Technologie der Goldgewinnung. Aufgrund der schweren Auswirkungen unkontrollierter Freisetzung von Zyanid in die Umwelt hat eine von der Europäischen Kommission eingesetzte Arbeitsgruppe die "best available techniques", kurz BAT, definiert. Für die internationale Vergleichbarkeit der Überlegungen in dieser Masterarbeit wurden außerdem die Empfehlungen des Australischen Umweltministeriums für das Management von Zyanid herangezogen.

Die bolivianische Goldmine Kori Kollo, betrieben von Empresa Inti Raymi S.A., sah sich im letzten Jahrzehnt mit schwerwiegenden Vorwürfen bezüglich massiver Umweltverschmutzung aufgrund mangelhafter Sicherheitsmaßnahmen konfrontiert. Um diesen überwiegend emotionalen, wenig wissenschaftlich fundierten Anschuldigungen eine unabhängige Analyse entgegenzuhalten, wurde die Umweltleistung der Goldmine untersucht und dokumentiert. Auf Basis der vor Ort erhobenen Daten erfolgte ein Vergleich des status quo mit den Referenztechnologien der BAT.

Folgende Kritikpunkte sind hervorzuheben: In der ersten Projektphase, dem Abbau von oxidischen Erzen, wurde zunächst der Untergrund für die Haufenlaugung nicht präpariert. Weiters muss die Integrität der behördlich vorgeschriebenen Berichterstattung aufgrund folgender Punkte in Frage gestellt werden: das Vorenthalten konkreter Messwerte, die Inkongruenz im Hinblick auf extern beauftragte Messungen und das Fehlen von Maßnahmen nach erhöhten Messwerten. Im Hinblick auf die zweite Projektphase, den Abbau von sulfidischen Erzen, liegt kein Nachweis von Kontaminierung durch die Bergehalden vor, allerdings sind die getroffenen Sicherheitsmaßnahmen nicht entsprechend der BAT dokumentiert. Außerdem wurden bei der Messung von Luftemissionen nur zwei Parameter untersucht (TSP-Gesamtstaub und PM-10), nicht aber die für eine umwelttechnische Einschätzung ebenfalls notwendigen Parameter wie z.B. die Form der Partikel und die chemischen Zusammensetzung des Staubes.

Zusammenfassend ist festzustellen, dass vor allem die mangelnde Nachvollziehbarkeit und Inkongruenz der Dokumentation und Berichterstattung kritikwürdig sind, die Planung der Goldmine Kori Kollo nach erster Einschätzung aber den Eindruck erweckt, den BAT annähernd zu entsprechen.

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Abstract

Cyanide Leaching at the Kori Kollo Gold Mine, Oruro, Bolivia:

Comparing the Environmental Performance to European Standards of Gold Extraction

Cyanide leaching of gold ores is the most commonly used technology for the extraction of gold. In response to severe impacts of uncontrolled release of cyanide or cyanide-containing waste into the environment, a technical working group implemented by the European Commission has defined BAT, i.e. "best available techniques". In order to achieve international comparability, a manual on "best practice cyanide management" commissioned by the Australian Federal Department of the Environment and Heritage was also consulted for this Master Thesis.

The Bolivian goldmine Kori Kollo, run by Empresa Inti Raymi S.A., has been confronted with strong criticism regarding severe environmental pollution due to neglecting safety measures. In order to balance these accusations, which largely lack scientific basis, the environmental performance of the goldmine was investigated and documented with an independent scientific analysis. Drawing on the locally acquired data, a comparison of the status quo with the guidelines of BAT was conducted.

The following points of criticism are paramount: The first phase of the project, the mining of oxidized ores, initially lacked the liner for the leaching pad. Moreover, the integrity of the legally required monitoring reports is questionable for the following reasons: the omission of reliable measured values, its inconsistency with externally commissioned measurements and the lack of response to elevated concentrations of pollutants. Regarding the second phase of the project, the mining of sulphide ores, no record of contamination by waste-rock exists, but the safety measures documented do not meet the BAT standards. In addition, monitoring of emissions to air only included two parameters (TSP and PM-10), neglecting the crucial parameters of particle shape and chemical composition of dust.

In summary, the gaps and inconsistency of the monitoring reports make it difficult to assess the environmental performance of the Kori Kollo goldmine. Precisely, the overall planning procedure seems to have been conducted with a technological standard approximating that of BAT.

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1 Introduction

Cyanide leaching of gold ores is the most commonly used technology for the extraction of gold, owing its predominant position to the exceptional properties of cyanide. The cyanide ion CN^{-} is a very effective chemical which allows most efficient recovery of gold on the one hand but on the other hand is very toxic to most living organisms including humans.

While in principle the-state-of-art of gold extraction provides measures and techniques to manage the environmental risks involved with cyanide leaching, the actual use of this chemical in the gold mining industry has shown deficiencies in the application of that knowledge on account of profit maximisation. As a consequence, environmental disasters have repeatedly occurred which raised aversion against that technology and may also have given room to populist politics in some cases.

1.1 Problem Identification

The enterprise Empresa Inti Raymi S.A. (EMIRSA) has been mining gold at the Kori Kollo mine in a surface mining operation since 1982 and continues to do so. The mining concept in use has been surface mining. The leaching plant has used cyanide from the beginning and was the first one of its kind in Bolivia on an industrial scale [1, Peró et al., 1992, pp.1-2]. In 2008 EMIRSA produced 2.7 t of gold [2, Storm, 2010] which accounted for approximately 30 % of Bolivia's overall mine production of gold in 2008 (8.4 t) [3, USGS, 2010a, pp.31.20-31.21].

EMIRSA has seen several changes of ownership during its operating life. At the time of the research stay carried out by the author of this Thesis (2007), the principal shareholder was the Newmont Mining Corporation (USA). In 2009 ownership turned 100 % Bolivian when the Newmont Mining Corporation sold its interests in EMIRSA. EMIRSA is presently controlled by Compañia Procesadora de Minerales S.A., Bolivia (88.0%) and one private shareholder, José Mercado Rocabado, Bolivia (12.0%). [2, Storm, 2010]

EMIRSA has been confronted with severe accusations concerning its environmental performance. Given that the majority of these accusations lacked a scientific investigation, the necessity for a scientifically grounded evaluation of the situation, such as carried out by this Thesis, was at hand.

Due to the severity of accusations referring to the phases of mining oxidized ores of the Kori Kollo hill (1985-1992) and of mining sulphide ores from the Kori Kollo pit (1992-2003) the environmental performance of the mine was investigated during the period of time between 1982 and 2003 (including the exploration phase) for the purposes of this Thesis.

1.2 Research Objectives

This Master Thesis aims at:

(1) Providing an overview of the state-of-the-art of the extraction of gold, focusing on managing the crucial aspects of acid rock drainage, tailings and waste-rock as well as cyanide.

(2) Investigating and documenting the environmental performance of the Kori Kollo gold mine (Oruro, Bolivia) from 1982 until 2003.

(3) Comparing the environmental performance at the investigated Kori Kollo goldmine from 1982 until 2003 to the state-of-the-art as specified for the purposes of this Thesis.

1.3 Methodology of Investigation

The methodology of investigation applied in the present thesis can be summarized in three parts:

(1) Local acquisition of data,

(2) Analysis of the state-of-the-art of gold extraction,

(3) Comparison and evaluation of collected data.

The author of this Thesis collected locally available data during a six-month research stay in Bolivia in 2007, as part of the EU-Programme ALFA/TECLIMIN1). The investigation of the Kori Kollo mine in Bolivia as a case study uses the Manifiesto Ambiental [4, Miller et al., 1997] dating from 1997 – including subsequent amendments [5, Miller et al., 1999] – as the main document of EMIRSA's environmental performance. The Manifiesto Ambiental provides information of both the affected area and the mining operation itself, including climate, geology and mineralogy, soil, subterranean water and surface water, flora, fauna, and socio-economic aspects and may be considered equivalent to an environmental impact statement according to Austrian legislature2).

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1) ALFA/TECLIMIN stands for América Latina Formación Académica/Tecnologías Limpias en la Industria Minero-Metalúrgica and may be translated to English as Latin America Academic Training/Clean Technologies in the Mining and Metallurgical Industry.

2) Article 6. (1) of the Federal Act on Environmental Impact Assessment [6, BMFLUW, 2000, Article 6. (1)] provides an extensive list on the required content of an "environmental impact statement" as part of an environmental impact assessment. The Act constitutes Austrian implementation of Community Law as of Council Directive 85/337/EEC on the assessment of the effects of certain public and private projects on the environment, as last amended by Council Directive 2003/35/EC [7, European Union, 2003].

In order to evaluate the environmental performance of the investigated mining operation, the "International Cyanide Management Code for the Manufacture, Transport and Use of Cyanide in the Production of Gold" (subsequently referred to as "ICMC") [8, ICMI, 2010] was used. "The Reference Document on Best Available Techniques (BAT) for Management of Tailings and Waste-Rock in Mining Activities" of the European Commission[3] [9, European Commission, 2009] was selected as the main benchmark. To facilitate international comparability, an Australian manual on "best practice cyanide management" [10, Needham, 2003] was chosen. As an additional source of information a technical report on treatment of cyanide heap leaches and tailings, published by the U.S. Environmental Protection Agency [11, USEPA, 1994] was consulted.

The present Thesis investigated the potencial discrepancies between international standards of gold production and local mining practice at the Kori Kollo gold mine.

In addition to the above mentioned documents the following selected sources of information were referred to:

(1) Official documents issued by EMIRSA: Published and/or handed in to national authorities, including:

- Lorax Environmental Services (2000): Lixiviación de óxidos en pilas: Fase V., La Paz, Bolivia: Empresa Minera Inti Raymi S.A. (Editor), 2000 [12, Lorax, 2000]

(2) Internal documents issued by EMIRSA which were not officially published:

- Batuani, P., Cardenas, V (2003).: Un ejemplo de minería, desarollo sostenible y responsibilidad social, CD-ROM. La Paz, Bolivia: Empresa Minera Inti Raymi S.A. (Editor), 2003 [13, Batuani & Cardenas, 2003]

- Peró, M., Meneses, C., Zelaya, O. (1992): El medio ambiente dentro de la actividad minera en la Empresa Minera Inti Raymi S.A. In: Peró, M. (Editor): *Proceedings of El Ambiente En La Minería 1992*. International seminar on The Environment in Mining. 18-19 May 1992, Santiago de Chile, Chile [1, Peró et al., 1992]

(3) References from the local scientific community:

- Montoya, J.C., Mendieta, R.S., (2006): Salinización y Metales Pesados – Evaluación ambiental de la mina Kori Kollo (EMIRSA) en el área de influencia, con aplicación de la Teledetección SIG, Oruro: Centro de Ecología y Pueblos Andinos (CEPA) (Editor), 2006. – ISBN 99954-30-18-5. [14, Montoya & Mendieta, 2006]

(4) References from personal communication with:

- EMIRSA staff.

- Members of Bolivian authorities
    - Ministry of Mining and Metallurgy, La Paz, Bolivia

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[3] Editor: European IPPC Bureau (EIPPCB) at the Joint Research Centre (JRC) at the Institute for Prospective Technological Studies (IPTS), Seville, Spain

        - Department of Environmental Issues.
    - Vice-Ministry of Rural Development, Farming and the Environment, La Paz, Bolivia
        - Department of Mining.
- Scientific staff of the following universities:
    - University of San Andrés, La Paz, Bolivia:
        - Institute for Metallurgy and Materials Research
    - Technical University of Oruro, Bolivia
    - University of Leoben, Austria
        - Institute for Sustainable Waste Management and Technology
        - Department of Metallurgy - Chair of Nonferrous Metallurgy
        - Department of Mineral Resources and Petroleum Engineering
            - Chair of Mining Engineering and Mineral Economics
            - Chair of Mineral Processing.

(5) Online information obtained during internet research conducted by the author

2 The Background of Gold Extraction

Gold has fascinated man for thousands of years. The Romans referred to the yellow metal as "aurum", in adoration of Aurora, the Roman goddess of the dawn [15, Waihi Gold, 2010]. "Aurum" stands for "shining dawn" and has been preserved until our times as the chemical symbol for gold, Au [16, Hoyt, 1985, p. 18-2].

This chapter provides information on the occurrence of gold and a brief introduction into the process of gold extraction. The section of the occurrence of gold is further divided into a description of the most important properties of gold, an overview of supply and demand, which describes recent production levels as well as recent trends of the top six gold producing nations worldwide and features an overview of global geological reserves of gold. The section is completed by displaying the fields and shares of the application of gold.

In the second section of this chapter an overview of the process of gold extraction is provided, including historical developments of gold extraction, mining concepts in use in gold mining, the use of cyanide in gold extraction – including a brief description of the chemistry and the toxicology of cyanide – and the unit operations of gold extraction.

2.1 Occurrence of Gold

According to Marsden & House, 2006 gold-bearing materials can be divided into primary ores and secondary materials. They can be classified into a total of 15 mineral processing-based categories which are related to their mineralogical and historical characteristics, as shown in Table 1 [17, Marsden & House, 2006, p. 26].

Table 1: Classification of gold-bearing materials, adapted from [17, Marsden & House, 2006, p. 26]

Primary ores	Secondary materials
Placers	Gravity concentrates
Free-milling ores	Flotation concentrates
Oxidized ores	Tailings
Silver-rich ores	Refinery materials
Iron sulphides	Recycled gold
Arsenic sulphides	-
Copper sulphides	-
Antimony sulphides	-
Tellurides	-
Carbonaceous ores	-

In accordance with the scope of the reference case study about the Kori Kollo mine, this Thesis focuses primarily on primary ores, which should by no means be taken as a statement of ignoring the significance of secondary metallurgy in gold production.

2.1.1 Properties of Gold

Gold belongs to the precious metals along with silver, platinum, palladium, iridium, osmium and rhodium. It owes its appreciation to its rareness[4)] and physical and chemical properties. [16, Hoyt, 1985, p. 18-2], [18, McQuiston jr, 1985, p. 18-2]

The appreciated properties of gold include the following aspects [16, Hoyt, 1985, p. 18-2], [17, Marsden & House, 2006, p. 19-21]:

- No tarnishing: Gold will not lose its shiny appearance.
- Excellent plasticity: Gold is very soft, malleable[5)] and ductile.
- Excellent electrical and thermal conductivity.
- Chemical inertness: Gold is among the most non-reactive (noble) metals.

Despite its low chemical affinity towards other elements, native gold usually occurs alloyed with silver. When the silver content amounts to 25-55 %, the mineral is referred to as electrum and has a pale yellow colour instead of the characteristic deep yellow (golden) colour of pure gold. The purity of gold in respect of the silver content can be expressed as fineness, as defined in equation [1] [17, Marsden & House, 2006, p. 21]:

$$fineness = \frac{(wt\%Au) * 1{,}000}{(wt\%Au + wt\%Ag)} \qquad [1]$$

(wt % Au …weight per cent gold, wt % Ag …weight per cent silver

The influence of silver and copper on the colour of gold is shown in Figure 1 where three levels of carat gold common in jewellery are indicated in dashed lines: 10 carat (Ct), 14 carat (Ct) and 18 carat (Ct) [17, Marsden & House, 2006, p. 26].

[4)] The average concentration of gold in the earth's crust amounts to 5 parts per billion (ppb) which corresponds to 0.005 [g/t] [17, Marsden & House, 2006, p. 19]

[5)] Malleable means capable of being extended or shaped by beating with a hammer or by the pressure of rollers [19, Merriam-Webster, 2010]. The mass unit for gold is troy ounces. One troy ounce accounts for approximately 31.10 g and can be beaten into an area of 30 m^2 [17, Marsden & House, 2006, pp. 20, 625]. The term "troy" is derived from Troyes, France, which used to be a mayor trading city of the Middle Ages [15, Waihi, 2010].

Carat gold is an alloy of gold and copper as the main components[6] [16, Hoyt, 1985, p. 18-3].

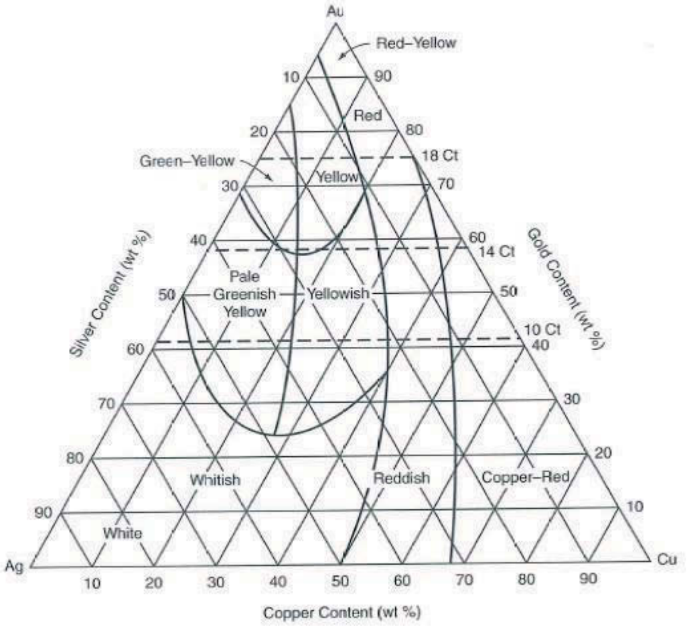

Fig 1: Gradation of colour of Au-Cu-Ag alloys [17, Marsden & House, 2006, p. 26]

2.1.2 Global Gold Supply and Demand

According to [21, Klapwijk, 2010] the global gold supply is composed of mine production, official sector sales and old scrap supply. In 2009 mine production accounted for approximately 2580 t, official sector sales for 40 t and old scrap supply for 1680 t, totalling up to approximately 4,300 t, with an expected rise to 4,500 t in 2010.

[21, Klapwijk, 2010] reported for 2010 (as of January 2010) a forecast average for gold prices of 1,170 [USD/oz troy] with top gold prices of 1,300 [USD/oz troy] possible. The new trend has had consequences on the three gold-supply-sectors: A year-to-year (2008 to 2009) comparison of the latter displayed the first annual increase in mine production for three years, as of approximately 160 t (plus 7 %). Official sector sales dropped by 200 t (minus 82 %), and old scrap supply increased by approximately 360 t (plus 27 %).

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[6] Carat is a measure of purity representing a fraction and is used for high-quality jewellery. One Carat is defined as 1/24 twenty-fourth part purity by mass, indicating the fraction of gold in the alloy. For example 14 carat gold consists of 58.3 % gold and 25 - 32 % copper and other metals in smaller fractions such as silver, zinc, platinum etc., depending on the requested properties for the piece of jewellery [16, Hoyt, 1985, p. 18-3]. It is not to be mistaken for the unit metric carat, which is a mass unit and is used to express the mass of gemstones. One metric carat equals 200 mg[20, USGS, 2010b, p.188]. The word "carat" derives from the Arabic word "qirat" for the fruit of the carob tree. The carob seeds were used by ancient traders as the means to balance the scales on oriental bazaars, which is why it became associated with jewellery [15, Waihi, 2010].

As for the global demand of gold, [21, Klapwijk, 2010] displayed the sectors: Fabrication, bar hoarding, net producer de-hedging and implied net investment. In 2009 demand increased so steeply that supply was sold to one hundred percent. However, the different sectors behaved differently to a significant degree from 2008 to 2009: Total fabrication decreased by approximately 470 t (minus 16 %), mainly caused by a sharp drop in jewellery fabrication by nearly 20 %, whereas other fabrication (including electronics and dentistry) decreased by only 5 %. Bar hoarding decreased by 200 t (minus 52 %), net producer de-hedging declined by roughly 100 t (minus 28 %) but implied net investment displayed a tremendous increase by 1,100 t (plus 333 %).

Mine Production of Gold in 2009

The ensuing section provides a brief overview of global mine production and geological reserves. In order to avoid confusion between the geological term for reserves and stocks of gold held, e.g. in banks – which are sometimes referred to as "reserves" as well – the term "geological reserves" is introduced in this Thesis which is understood as a synonym to the term reserves defined by U.S. Geological Survey (USGS)7). Figures were taken from two USGS publications. The Mineral Commodity Summaries 2010 [20, USGS, 2010b, p.67] provided the most recent estimates for 2009 whereas the overview from 2004-2008 was obtained from The Minerals Yearbook Gold 2008 [3, USGS, 2010a, pp.31.20-31.21]. USGS figures differ slightly from figures reported by Klapwijk. Taking into account that estimates carried out by different institutions are naturally prone to a certain degree of deviation, the difference lies within scientifically acceptable range.

In 2009 the global mine production of gold amounted to a total of 2,350 t. The EU-27 is not significant as a gold producer8) on a global scale. As a consequence the EU-27 is not included in the discussion of amounts and trends of gold production in the present and the ensuing section. The top six gold producing nations in 2009 were (in top-down order): China (300 t), Australia (220 t), South Africa (210 t), the United States of America (USA) (210 t), Russia (185 t) and Peru (180 t). Notably, South Africa and the USA took third position in equal measure. The top six nations were responsible for more than half of the total global production (1,305 t). Figure 2 shows a world map indicating the top six gold producing nations in 2009.

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[7] See section Global Geological Reserves of Gold in 2009 for further terminology

8) [3, USGS, 2010a, pp.31.20-31.21] reported total gold mine production for 2008 in the EU-27 as of approximately 23 t with Sweden (5t), Finland (5t) and Bulgaria (4t) as the top European gold producing nations.

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Fig 2: Top six gold producing nations in 2009 on the world map

Trends in Mine Production of Gold from 2009 to 2004

The top six (by mass) gold producing nations are subsequently discussed from a standpoint reviewing the years backwards from 2009 to 2004. Table 2 displays the gold production in tons [t] by nation, the top six nations and in world total. The key figures determining the ranking are marked in bold letters and are described subsequently. Comparatively, Bolivia took only 29th position (8 t) in 2008 in the ranking of gold producing nations. For 2009, no data on Bolivian gold production were available.

In 2009 the world trend of decreasing mine production ended, as [21, Klapwijk, 2010] reports (see above). China extended its leading position by pushing mine production to 300 t. Russia continued its rise in mine production and finally replaced Peru in fifth position, which Peru had held for several years. That is why Russia – the long-time sixth position in this ranking – was also included in the discussion.

In 2007 global mine production remained static compared to 2006, as of 2,370 t. China took over the lead of gold producing nations by producing a total of 275 t from its gold mines. The long-time first position nation South Africa was replaced by China because of unfavourable conditions9) over several years.

The year 2006 (2,370 t) saw a decrease in global mine production of 100 t compared to 2005 (2,470 t), which set off a downward trend. Only China showed a rise in mine production (2006: 245 t compared to 2005: 225 t), defying the global trend.

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9) Power outages, closure of shafts owing to mine accidents and ongoing problems with labour force cf. [3, USGS, 2010a, p.31.9].

Comparatively, precisely in 2006, in contrast to the global trend as well, Bolivia reported the highest mine production (10 t) within the investigated years 2009 to 2004.

A year-to-year comparison of 2005 and 2004 displayed a trend of moderate increase in global mine production, which was followed by Australia, China and Russia. Peru showed a steep increase in mine production. Contrariwise, South Africa suffered a landslide drop.

Table 2: Top six gold producing nations from 2009-2004, including Bolivia on 29th position in 2008, adapted from [3, USGS, 2010a, pp.31.20-31.21], [20, USGS, 2010b, p.67]

Ranking	Country	**2009**	2008	**2007**	**2006**	**2005**	2004
2009	**World**	**2,350**	2,280	2,370	**2,370**	**2,470**	2,420
-	Top 5	1,125	1,122	1,170	1,175	1,202	1,232
1	**China**	**300**	285	**275**	**245**	225	215
2	Australia	220	215	247	247	262	259
3	**S-Africa**	210	213	253	272	**295**	**337**
4	USA	210	233	238	252	256	258
5	**Russia**	**185**	176	157	159	164	163
6	Peru	180	180	170	203	**208**	**173**
29(1)	Bolivia	N.d.a.(2)	8	9	10	9	7

(1)… Bolivia took 29th position in 2008, as of most recent available data
(2)… N.d.a.…No data available

Global Geological Reserves of Gold in 2009

USGS terminology distinguishes numerous terms on the subject of "resources" and "reserves". In the frame of this Thesis, "resources" are referred to concentrations of naturally occurring solid material in such form that economic mining is currently or potentially feasible. "Reserves" require economic extraction at the time of determination, ruling out potentially mineable material. For further definitions confer [20, USGS, 2010b, pp.189-190].

Estimates of global geological reserves of gold amount to 47,000 t. The greatest geological reserves of gold are found in South Africa10) (6,000 t), followed by Australia (5,800 t), Russia (5000 t), the USA and Indonesia (both 3,000 t). The top six nations provide almost half (22,800 t) of the geological reserves of gold. China (1,900 t), the leading gold producing nation since 2007, takes eighth position in geological reserves of gold. [20, USGS, 2010b, p.67]

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10) Johannesburg is embedded in the Witwatersrand basin, which hosts the greatest gold resource in the world [SME 2006 p. 4].

2.1.3 Application of Gold

The major application of gold has been in jewellery and decoration since ancient times until today [17, Marsden & House, 2006, p.1].

According to [21, Klapwijk, 2010] the total amount of gold ever mined, also referred to as above-ground stocks, was estimated to be 166,000 t at the end of 2009. Jewellery accounted for 52 %. The rest of above-ground stocks were held by private investment, 18 %, official holdings, 16 % and other fabrication (including electronics and dentistry), 12 %. It is estimated that around 2 % of all mined gold have been lost and unaccounted for during gold production, see Figure 3.

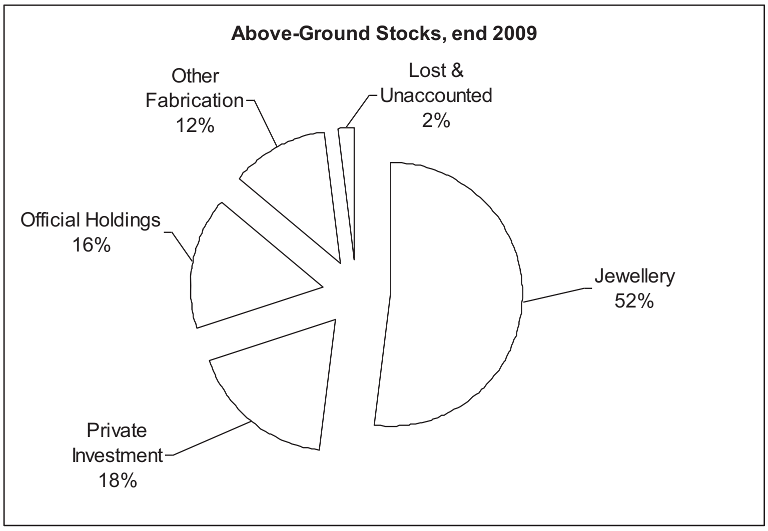

Fig 3: Above-Ground Stocks, end 2009 [21, Klapwijk, 2010]

2.2 The Process of Gold Extraction

Many methods used in gold extraction today are based on discoveries made a very long time ago, such as gravity concentration. On various occasions, rediscovery of old technology was combined with contemporary improvements, resulting in an increase in overall efficiency. With many questions and challenges still unanswered – e.g. an alternative to cyanide leaching in favour of less hazardous technologies – an understanding of the historical background of gold extraction is essential, as it may help to shape the future. However, the scope of this Thesis allows only a selected access to the history of gold extraction and refers to the available literature11) for a more detailed disquisition of the subject. [17, Marsden & House, 2006, p.1]

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11) A valuable list of references is provided by [17, Marsden & House, 2006]

2.2.1 Historical Developments of Gold Extraction

On the basis of the importance of the use of cyanide in gold mining and the first industrial application of cyanide leaching in 1889[12], the history of gold extraction may be divided into two phases [17, Marsden & House, 2006, p.1]:

- Precyanidation: prior to 1888,
- Cyanidation: 1889 until today.

Precyanidation

The history of gold extraction goes back until around 10,000 BC, when man used gold recovery methods such as collection by hand and gravity concentration from streambeds. [17, Marsden & House, 2006, p.1]. [17, Marsden & House, 2006, p.14] dated back the discovery of amalgamation of gold with mercury to 1,000 BC.

In 1848 the capability of chlorine gas to convert gold into the water-soluble gold trichloride was discovered. Chlorination was a cost-intensive process, requiring a cut-off[13] gold of about 50 [g/t]. The high costs of chlorination and the required content of gold finally cleared the way for cyanidation, which is capable of mining ores with only one percent of the cut-off gold required by chlorination (see section Extracting on p. 26), to become the principal gold extraction technique. [17, Marsden & House, 2006, pp.1,5].

Cyanidation

In 1887 the first patent for cyanidation was registered by J.S. MacArthur in Great Britain, which drew on studies of dissolution of gold in potassium cyanide solutions by L. Elsner in 1846. Although Elsner did not relate his discovery to the extraction of gold, the equation by which the process is commonly demonstrated today still bears Elsner's name. [22, Herz, 1985, p. 18-3].

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[12] The first cyanidation plant in the world was established in 1889 at the Crown Mine at Karangahake, New Zealand [10, Needham, 2003, p.113]

[13] The economically required amount of gold to be retrieved, see chapter extraction

Nowadays cyanide is used as a lixiviant for gold all around the world. In 2000, more than half (52 %) of the gold or gold and silver mining operations in the world used cyanide[14)] – excluding base metal mines where gold is recovered as a side product at the mine itself or at the smelter. The remaining 48% did not abandon cyanide in favour of an alternative chemical reagent but for lack of need of a lixiviant. Ore dressing by gravity separation and flotation may have been sufficient in those cases to form a concentrate. [9, European Commission, 2009, p.16]

2.2.2 Concepts for Mining of Minerals

The extraction of ore is referred to as mining. Ore is the material of interest in the mineral extracting industry. It consists of a mineral or a variety of accumulated minerals of sufficient value as to quality and quantity that it may be mined at a profit [9, European Commission, 2009, p.459]. There are four basic concepts for mining of minerals [9, European Commission, 2009, p.41]:

- Surface mining
- Underground mining
- Quarry
- Solution mining

The choice of method depends on many factors, such as:

- Characteristics of the mineral
    - Value of the mineral
    - Grade of ore
- Characteristics of the ore-body
    - Site location
    - Size, form and depth
    - Geological, hydrogeological and geomechanical conditions of the rock mass
- Characteristics of the (surrounding) area
    - Land availability

[14)] The predominant application of cyanide in the mining industry was also emphasized by Needham, 2003 reporting that two-thirds of the worldwide NaCN production was employed in that sector, pointing out cyanide leaching in gold and silver extraction as the main utilization [10, Needham, 2003, p.70].

  - Surface constraints
  - Seismic conditions
  - Environmental conditions
  - Environmental impact of the operation

The last two of the four above mentioned mining concepts, i.e. quarry and solution mining, are mainly applied in the extraction of construction material, such as gravel, and industrial minerals, such as talc [23, Tiess, 2010]. The two main concepts which are in use for the extraction of gold are surface mining and underground mining which are briefly described in the ensuing subchapter.

2.2.3 Concepts for the Mining of Gold

Figure 4 and Figure 5 indicate the two main concepts for the extraction of gold: Surface mining and underground mining. In many cases, the uppermost part of an ore-body is mined by surface mining. When applying this mining concept the ore-body needs to be reached by removing all of the material covering the ore-body, including vegetation, top soil and rock, the latter of which is commonly referred to as overburden (see red marking in Figure 4). As a consequence huge amounts of waste-rock15) are generated16). [9, European Commission, 2009, pp.41, 42]

When the removal of overburden makes this mining concept uneconomical, mining may be continued underground. The main advantage of underground mining consists of mining the ore more selectively by constructing a shaft and drifts (see Figure 5). As a consequence, top soil and overburden material remain untouched and areas of waste-rock and low grade ore can mostly be left out. In addition to the advantage of keeping the amounts of generated waste-rock smaller, the material can also be disposed of underground by backfilling it into mined out areas. [9, European Commission, 2009, p.44]

However, compared to surface mining, operation costs for underground mining are significantly higher. Other reasons why underground mining is often ruled out [9, European Commission, 2009, p.44] involve:

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15) According to [9, European Commission, 2009, p.462], the term waste-rock refers to a part of the ore-body which cannot be mined and processed profitably for lack of existing ore. For the purposes of this Thesis, the term waste-rock includes overburden, as it consists of rock as well and comprises a considerable amount of waste.

16) According to the Eurostat yearbook 2009 more than 700 million tonnes of mining and quarrying waste is estimated to have been generated in the year 2006 in the EU-27. [24, Eurostat, 2010, p. 438]

- The processing plant was designed for larger tonnages that were obtainable by surface mining but are not possible any more in underground mining. This results in decreasing overall efficiency of the operation.
- Lack of continuity of the ore-body requires unjustifiable effort in the construction of the shaft and the drifts.
- Rock stability is an important issue in underground mining and may impede any underground mining operation.

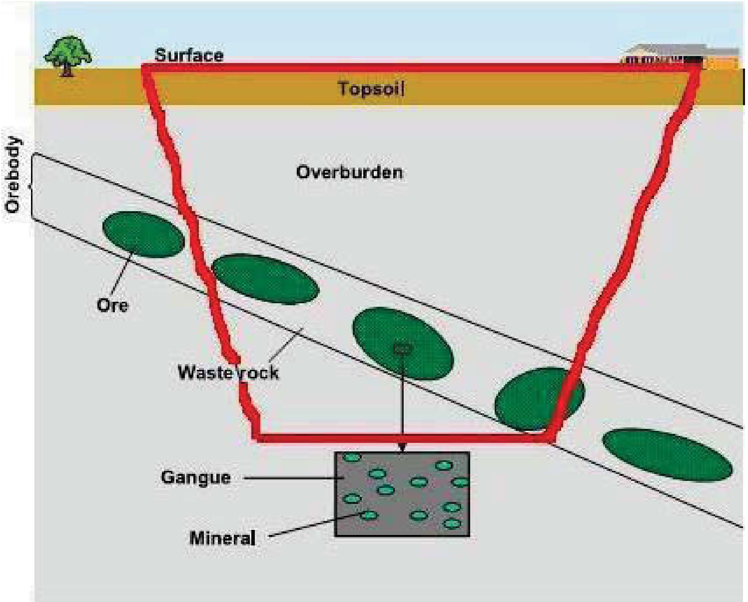

Fig 4: Schematic drawing of a surface mining operation, adapted from [9, European Commission, 2009, p.43]

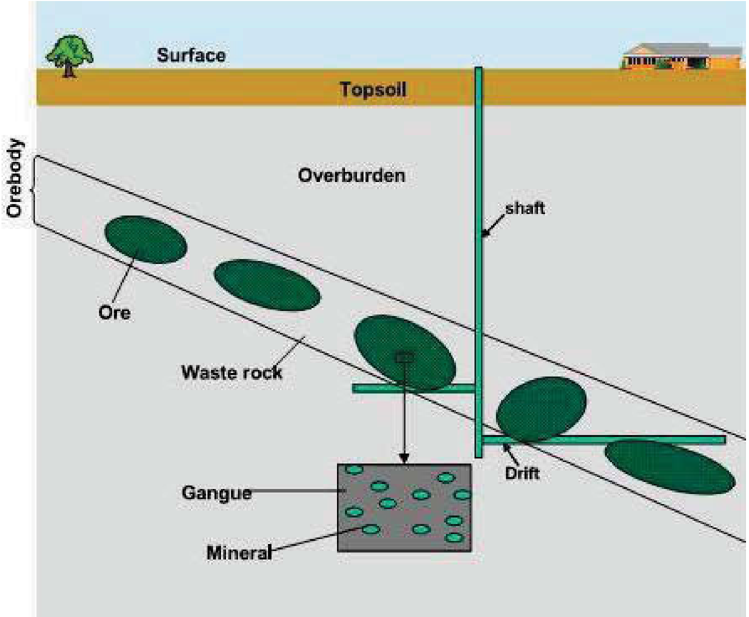

Fig 5: Schematic drawing of an underground mine [9, European Commission, 2009, p.43]

2.2.4 The Use of Cyanide in Gold Extraction

Cyanide is mainly[17] used for leaching gold and silver ores[18]. It is a very effective substance from the chemical point of view. Before cyanidation was introduced into gold extraction in the late 19th century (see subchapter 2.2.1 Historical Developments of Gold Extraction), gold recovery ranged between 40 %-50 %. With the aid of cyanide, gold recovery improved to 85 %-95 % [10, Needham, 2003, p.113].

The chemical effectivity of cyanide also accounts for negative effects. It is very toxic for many plants and creatures (including humans), as will be discussed in subchapter The Toxicology of Cyanide. With global gold demand being higher than supply levels (see subchapter 2.1.2 Global Gold Supply and Demand) and presently no technical alternative that can economically outmatch the use of cyanide in gold production [10, Needham, 2003, p.7], the only option lies in responsible application of this powerful, yet hazardous chemical, which will be the topic in subchapter Management of Cyanide.

The first measure in responsible application of cyanide consists of information. By attaining an understanding of the properties of cyanide, subsequent measures like training, proper handling and as a consequence a safe and also cost-efficient use of this tool become possible. Bearing this in mind, the ensuing section is set out to provide a brief introduction to the properties of cyanide.

2.2.4.1 The Chemistry of Cyanide

> "Cyanide is a singly-charged anion containing unimolar amounts of carbon and nitrogen atoms triply-bonded together: $C\equiv N^{-}$" [25, Young, 2005, p.104].

In some technical literature the term cyanide refers to any chemical compound which contains the cyano group ($C\equiv N$) [26, Noller, 2008, p.1].

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[17] Cyanide is also used for other processes in the extraction of metals. For instance, it may be added in the separation of sulphide minerals by flotation as a depressant for pyrite (FeS_2). Moreover, cyanide is also used in metallurgical applications, e.g. in treating the surfaces of metal products [25, Young, 2005, p.105].

[18] Young reported that over a billion tons of gold ore were leached each year with cyanide. [Young 2005 p 105]

The Formation of Hydrocyanic Acid

Cyanide ions hydrolyze in water according to equation [2] [17, Marsden & House, 2006, p.234]

$$CN^- + H_2O \Leftrightarrow HCN(aq) + OH^- \qquad [2]$$

The reaction of hydrolysis also produces hydroxyl (OH^-) ions which results in an elevated pH-value of the solution. Hydrogen cyanide in aqueous solution is a weak acid referred to as hydrocyanic acid (HCN) (aq). It dissociates in water according to equation [3] [17, Marsden & House, 2006, p.234]

$$HCN(aq) \Leftrightarrow H^+ + CN^- \qquad [3]$$

Where $K_a(25°C) = 6.2 \times 10^{-10}$, $pK_a = 9.31$ K_a…dissociation constant

The dissociation reaction is dependent on pH through the formation of hydrogen ions H^+. Figure 6 displays the speciation of CN^- and HCN in an aqueous solution as a function of pH. At approximately pH 9.3 equation [3] is in equilibrium and CN^- and HCN are present at equal shares of 50 %. At pH 10.2, 90 % of the total cyanide is present as CN^-. Correspondingly, more than 90 % of the total cyanide is present as HCN at pH 8.4. [17, Marsden & House, 2006, p.234]

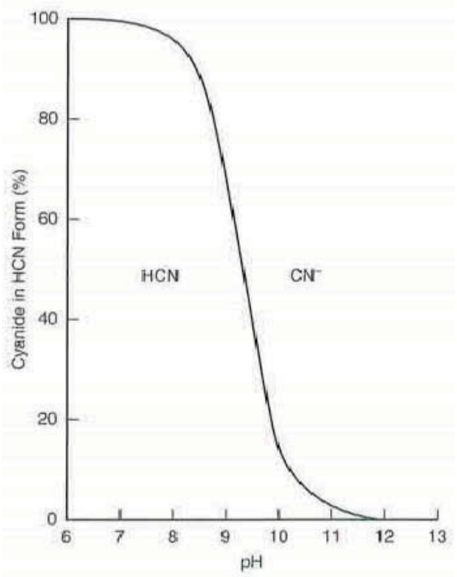

Fig 6: Concentrations of HCN and CN^- in aqueous solution as a function of pH [17, Marsden & House, 2006, p.235]

Natural Degradation of Cyanide

The dissociation of HCN (aq) is all the more important due to the high vapour pressure[19] of HCN(g) which facilitates volatilization on the liquid surface, according to equation [4] [17, Marsden & House, 2006, p.234]

$$HCN(aq) \Rightarrow HCN(g) \qquad [4]$$

Volatilization of HCN is disadvantageous during leaching on account of two reasons. First and foremost, the emission of highly toxic HCN gas causes a problem for operator safety. Secondly, from the standpoint of leaching, gaseous HCN is lost to the ambient air and therefore winds down efficiency of the operation. However, when it comes to natural degradation and loss of cyanide from tailings facilities, this effect can be desirable from the environmental point of view. According to [10, Needham, 2003, p.17] volatilization of HCN is the main process of natural loss (attenuation) of cyanide. Processes such as microbial generation of cyanate and ammonia, hydrolysis in soils, anaerobic biodegradation and complexation (see next section) may also naturally reduce the cyanide concentration [11, USEPA, 1994, p.17].

The Formation of Stable Metal Complexes

The cyanide ion (CN^-) is a strong ligand, capable of complexing at low concentrations with virtually any heavy metal. It is precisely the affinity of forming stable metal complexes that causes the toxicity of cyanide to plants and creatures: whenever heavy metal ions are bound into cyanide complexes their transport through tissues is inhibited. As a consequence, the organism is deprived of the heavy metal's function within its system (see also subchapter 2.2.4.4 The Toxicology of Cyanide). [25, Young, 2005, pp.104-105]

2.2.4.2 Classification of Cyanide

Cyanide forms both organic and inorganic compounds. With respect to the subject of this Thesis, organic cyanides are not discussed here, despite their significance in numerous other applications[20].

[27, Klenk et al., 1987, pp.159-190] specified four groups of inorganic cyanide compounds:

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[19] Hydrocyanic gas HCN(g) has a vapour pressure of 100 kPa at 26ºC, which is approximately three times higher than the vapour pressure of water (34 kPa at 26ºC) [25, Young, 2005, p.106]

[20] Among many others, organic cyanides are involved in products such as chelating agents, e.g. ethylendiaminetetraacetic acid (EDTA) and polymer chemistry, e.g. nylon [27, Klenk et al., 1987, pp.164-165]

- Hydrogen cyanide (HCN)
- Metal cyanides
- Cyanogen halides (halogen cyanides)
- Cyanogen

Metal cyanides are relevant for the extraction of gold. The formation of HCN is a non desirable side product, the properties of which were dealt with in subchapter The Chemistry of Cyanide.

The U.S. Environmental Protection Agency sub-classified cyanides into six groups, according to their stabilities in water, as shown in Table 3 [11, USEPA,1994, p.20]:

- Free cyanide (CN^{-}_{FREE})
- Simple cyanides readily water soluble
- Simple cyanides relatively water insoluble
- Weak complexes
- Moderately strong complexes
- Strong complexes

Table 3 displays examples of cyanides from gold and silver processing solutions and their categorization as which are marked as "X" as specification applies and as "-" as specification does not apply. For a definition of CN^{-}_{TOT}, CN^{-}_{WAD} and CN^{-}_{FREE} see subchapter 2.2.4.3 Terminology of Analytical Determination of Cyanide.

Table 3: Relative stabilities of cyanide complexes in water present in gold and silver processing solutions, adapted from [11, USEPA,1994, p.20]

Cyanide species	**Cyanide examples**	CN^{-}_{TOT}	CN^{-}_{WAD}	CN^{-}_{FREE}
Free cyanide	CN^{-}, HCN	X	X	X
Simple cyanides readily water soluble	NaCN, KCN, $Hg(CN)_2$, $Ca(CN)_2$	X	X	-
Simple cyanides relatively water insoluble	CuCN, $Ni(CN)_2$, AgCN	X	X	-
Weak complexes	$Zn(CN)_4^{2-}$, $Cd(CN)_5^{3-}$ $Cd(CN)_4^{2-}$	X	X	-
Moderately strong complexes	$Cu(CN)_4^{2-}$, $Cu(CN)_3^{2-}$ $Ni(CN)_4^{2-}$, $Ag(CN)_3^{2-}$	X	X	-
Strong complexes	$Fe(CN)_6^{4-}$, $Co(CN)_6^{4-}$ $Au(CN)_5^{2-}$	X	-	-

Simple and Complex Metal Cyanides

[27, Klenk et al., 1987, p.165] described metal cyanides, which are used in mining as the source of CN^-, as one or more CN^- bonded as ligands to metal ions. Depending on the number of metals and the kind of metal forming the cyano-metal complex, they can be classified into simple cyanides and complex cyanides.

In equation [5] simple cyanides are represented as $M(CN)_X$, where M is a metal and x is the number of CN groups, according to the valence of M. [27, Klenk et al., 1987, p.165]. For example in NaCN, x equals one.

The solubility in water ranges from readily soluble to relatively insoluble, depending on the type of metal, pH (see equation [2] on p. 19) and temperature (see Table 3 on p. 21). Simple cyanides dissociate into metal cations and cyanide anions, according to equation [5].

$$M(CN)_x \Leftrightarrow M^{x^+} + xCN^- \qquad [5]$$

Complex cyanides can be described as $A_y[M(CN)_X]$. A is either an alkali metal or alkaline-earth metal, or heavy metal. Y is the number of ions of A. M is usually a transition metal. X is the number of CN-groups. Generally speaking, complex cyanides are highly water soluble when A is an alkali or alkaline-earth metal and insoluble when A is a heavy metal. [27, Klenk et al., 1987, p.165]

2.2.4.3 Terminology of Analytical Determination of Cyanide

Cyanide is usually analytically determined as one of three forms (i.e. species):

- Free cyanide (CN^-_{FREE})
- Weak acid dissociable cyanide (CN^-_{WAD})
- Total cyanide (CN^-_{TOT}).

Free cyanide (CN^-_{FREE}) refers to the sum of cyanide ions (CN^-) and hydrogen cyanide (HCN) present in solution, including cyanide-bonded sodium, potassium, calcium or magnesium [11, USEPA, 1994, p.19]. The free cyanide ion CN^- is generally the measure after sample treatment [10, Needham, 2003, p.14].

CN^-_{WAD} is the fraction of cyanide volatilized as HCN when pH is lowered to 4.5 (see equation [2] on p. 19) by administering a weak acid buffer solution (e.g. sodium acetate/acetic acid). CN^-_{WAD} encompasses CN^-_{FREE}, simple cyanides, weak cyanide complexes of zinc and cadmium and moderately strong complexes of silver, copper and nickel.

CN^-_{TOT} measures the sum of all cyanide present in a system [11, USEPA, 1994, p.19].

Analytical methods used to determine cyanide concentrations are widely debated in the technical literature. USEPA, 1994 reported inconsistencies in the 1990ies as far as analytical methods used to determine cyanide concentrations were concerned. A change from CN^{-}_{FREE} to CN^{-}_{WAD} as standard measurement in regulations was discussed in the USA. CN^{-}_{FREE} was reported to show deficiencies in accuracy while CN^{-}_{WAD} was acclaimed for easier determination at concentrations below 1 part-per-million (ppm). [11, USEPA, 1994, p.19]

[10, Needham, 2003, p.14] denied the toxicological value of analysing for CN^{-}_{TOT} due to the required harsh sample treatment (to break down strong complexes into measureable CN^{-}_{FREE}), which could destroy some cyanide and therefore alter the measurement and argued further that CN^{-}_{WAD} was the best measure for assessing human and animal toxicity.

2.2.4.4 The Toxicology of Cyanide

The free cyanide ion CN^{-} is the active agent in both the leaching process and the toxicological effect to biological systems [10, Needham, 2003, p.3]. As a consequence the toxicity of a cyanide compound depends on the amount of CN^{-} released, i.e. its disposition to release CN^{-} and its present concentration in the affected medium.

In metal cyanides the ability to set free CN^{-} is expressed as a function of the bond strength between the metal atoms and the ligand cyanide-functional group. The lower the bond strength, the easier CN^{-} is released and the more toxic the compound acts. Consequently, water soluble simple cyanides like NaCN have a high toxicological potential whereas strong (water insoluble) complexes like $Co(CN)_6^{4-}$ are non toxic (cf. Table 3 on p. 21). [11, USEPA, 1994, p.20]

The Toxicity of Cyanide

Cyanide is toxic out of two paramount reasons: Firstly, CN^{-} impedes cell respiration and secondly CN^{-} acts very quickly due to its low stability and therefore high mobility.

The first reason why cyanide acts as a poison is based on the elevated chemical affinity of CN^{-} towards iron, which facilitates the forming of a cyanide-iron-complex. Iron is present within the enzyme cytochromoxidase, which carries out the last step in the respiratory chain. By binding iron within the complex, the enzyme is blocked and the respiratory chain is interrupted. The tissues cannot take up oxygen from the blood any more, even if oxygen is available. As a consequence the affected cell suffers from oxygen starvation and finally dies. [10, Needham, 2003, p.22], [28, Menapace, 2007, p.66]

The second reason refers to the "lethal efficiency" of cyanide, i.e. the amount of substance and the time needed to develop a cyanide-intoxication. As far as human and animal organisms are affected, the cyanide uptake can take place by three pathways [27, Klenk et al., 1987, p.184]:

- Absorption through the eyes, skin and mucous membranes.
- Inhalation through the respiratory system
- Oral ingestion

Upon inhalation the first symptoms of intoxication occur within seconds. Oral ingestion of cyanides approximately takes a few minutes to show effect. [28, Menapace, 2007, p.66]

[27, Klenk et al., 1987, p.184] reported that high cyanide concentrations in the blood stimulate the respiratory centre, leading to an enhanced uptake of cyanide by inhalation and hence exacerbating cyanide's toxic effects.

2.2.4.5 Cyanidation — The Extraction of Gold with the Aid of Cyanide

The cyanide ion has an affinity for complexing with heavy metals (see section The Formation of Stable Metal Complexes on p. 20). In ore dressing, this property is utilized, whereupon cyanide forms very stable gold-cyanide complexes, which are subsequently recovered from the pregnant solution, as described in the ensuing subchapter. The dissolution of gold and forming of gold-cyanide complexes is dependent on oxygen and demonstrated by Elsner's equation in equation [6] [18, McQuiston, 1985, p. 18-6]

$$4Au + 8NaCN + O_2 + 2H_2O \rightarrow 4NaAu(CN)_2 + 4NaOH \qquad [6]$$

2.2.5 Unit Operations of Gold Extraction

There is no single operations flow-sheet of gold extraction. Gold bearing minerals feature very distinctive characteristics which require process selection to be tailored to every deposit individually. Nevertheless, most flow-sheets of gold extraction contain the following unit operations (adapted from [15, Waihi Gold, 2010]):

- Prospecting and exploration
- Extracting
- Processing
- Refining
- Waste management
- Closure
- Recultivation

In view of the aims of this Thesis, technical procedures will only be described to the extent necessary for defining the state-of-the-art of gold extraction according to EU-standards [9, European Commission, 2009]21).

These standards will be used as the basis for an evaluative comparison with the unit operations identified and described in the quoted case-study (see subchapter 4.3 Comparing the Environmental Performance to European and Non-European Standards).

Prospecting and Exploration

The aim of prospecting and exploration is to find deposit of gold which economically allows setting up a mining operation. In the prospecting phase a selected part of the earth's crust which satisfies the geological criteria necessary for the concentration of the desired mineral is scanned. The exploration phase continues the search by assaying the identified deposit for mineralogical properties.[29, Tiess, 2010, p.8]

The laboratory assay requires core samples of rock from the target area taken from different levels of depth which are obtained by drilling. The samples are subsequently assayed to determine the mineralogical composition and hence the location of ore and waste material. [15, Waihi Gold, 2010]

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21) Detailed descriptions of the technology of gold extraction can be found in technical literature, e.g. [17, Marsden & House, 2006]

Further testing and research is required in order to assess the potential environmental and social impacts of a mining operation before regulatory approval can be obtained. As soon as the Mining Licence and Water Rights are granted by the competent authorities, mining moves on to the extraction process.

Extracting

There are two kinds of material within the deposit: ore and waste-rock. The economically required amount of gold to be retrieved is referred to as cut-off [g/t] gold which stands for grams of gold retrieved at the rate of mined tons of ore [30, Flachberger, 2010]. The cut-off gold depends on several factors, including social and environmental aspects as well as the characteristics of the host mineral, which consequently determine the mining technology applied and which finally comprise the gold price on the global market.

In 2008, AngloGold Ashanti, a gold mining enterprise based in South Africa, reported cut-off [g/t] gold in a surface mining operation in Colombia between 0.3 [g/t] and 0.5 [g/t] related to gold prices between 700 [USD/oz troy] and 1.000 [USD/oz troy] respectively, as can be seen in Table 4 [31, AngloGold Ashanti, 2008, p.1].

Table 4: Cut-Off [g/t] gold in surface mining related to gold prices [USD/oz troy] for the La Colosa deposit in Colombia, adapted from [31, AngloGold Ashanti, 2008, p.1]

Grade [g/t]	Cut-Off [g/t]	Price [USD/oz troy]
1.03	0.5	700
0.95	0.4	800
0.86	0.3	1,000

With gold prices currently exceeding by far 1.000 [USD/oz troy][22] areas with even lower gold grades could become feasible. With higher production costs in underground mining, ore-bodies are required to provide cut-off [g/t] gold in the order of magnitude of 3 [g/t] when that mining concept is applied [31, AngloGold Ashanti, 2008, p.8].

The localization of ore and waste-rock is done by sampling and assaying similar to the exploration phase. In surface mining the results of this geological and mineralogical pre-examination are used to mark areas of ore and waste-rock on the pit floor, which allows the selective extracting of ore [15, Waihi Gold, 2010]. In underground mining, the localization of ore and waste-rock are used to determine the position of the shaft and the drifts, in order to reach ore areas as accurately as possible [9, European Commission, 2009, p.44].

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[22] [32, World Gold Council, 2010] reports 1,368.9 [USD/oz troy] on November 14, 2010

In both surface and underground mining, drilling and blasting is applied to break up hard rock. Transportation to the processing unit in the case of ore and to the waste-rock deposit in the case of waste-rock is carried out by conveyor belts or trucks [15, Waihi Gold, 2010]. The unprocessed broken ore is referred to as run-of-mine [17, Marsden & House, 2006. p 79].

Water management is crucial to every mining operation. Some aquifers lie only a few meters below the surface. As a consequence, subterranean water needs to be pumped out continuously. The amounts of water to be dealt with can be quite significant. As the quality of this water may be poor (e.g. due to high levels of dissolved solids, see also case study in subchapter 4.2.2.2 Mining of Sulphide Ores of the Kori Kollo Hill) it is often used to wash vehicles on site and sprayed on haul roads as a measure of dust emission prevention. Excess water requires proper treatment to be pumped to the water treatment unit prior to being used as process water or being discharged to a recipient (if available). Alternatively, excess water is discharged to the tailings management facility (TMF) without treatment. [15, Waihi Gold, 2010]

Processing

Gold occurs both as native gold, which is also referred to as free-gold, and finely dispersed within rock of no interest [9, European Commission, 2009, p.14]. In order to ensure best gold recovery, the ore needs to be prepared. The valuable minerals that contain gold need to be liberated by crushing and grinding. Given that the coarse particles of free-gold naturally take longer to dissolve, they need to be separated before leaching by gravity-concentration in order to decrease the bulk feed for the leaching circuit. [8, ICMI, 2010]

Leaching with an aqueous cyanide solution is carried out by two independent methods today: heap leaching and tank leaching. In **heap leaching** the ore is piled up on a pad that has been prepared with a liner. The liner consists of layers of compacted impermeable soil, a drainage layer and a geotextile membrane made of high density polyethylene (HDPE). The cyanide solution, which contains cyanide concentrations in the range between 300 and 500 [mg/l] (as of 100 % NaCN), is applied to the heap by a sprinkling system. [8, ICMI, 2010]

The gold-laden solution, also referred to as pregnant solution, is collected and transported to the processing plant for gold recovery. Leaching times may range between days and months which constitutes a drawback of the method. Overall gold recovery is also low for cyanide leaching, ranging between 50 and 75 %. The main advantage of the method is its low capital cost. [11, USEPA, 1994, p.1] reported that heap leaching was used for beneficiation of gold grades smaller than 1.24 [g/t]. Correspondingly, tank leaching is used for gold grades greater than 1.24 [g/t]. [8, ICMI, 2010]

Tank leaching involves grinding the ore very finely to make it amenable for subsequent leaching in tanks. The necessary oxygen (see Elsner's equation [6] on p. 24) is provided by pumping air, oxygen or hydrogen peroxide into the tank. A binding operating condition is pH control. In order to maintain cyanide in the solution, lime is added to ensure a pH of 10-11 (see subchapter 2.2.4.1 The Chemistry of Cyanide). [8, ICMI, 2010]

Recovery of dissolved gold from the pregnant solution or the leaching slurry uses either **cementation on zinc powder** (Merrill-Crowe-Process) or **adsorption on activated carbon**. The Merrill-Crowe-Process produces a gold precipitate which is already marketable or is dried and smelted to raw gold. The activated carbon may be added to the pulp in the same tank during the leaching process (referred to as carbon-in-leach CIL) or after leaching in a separated tank (referred to as carbon-in-pulp CIP). Gold adsorbed on activated carbon is screened from the slurry, stripped by a hot caustic aqueous cyanide solution and recovered by electrolysis. The product is referred to as doré (an alloy of gold and silver) and contains between 70 % and 90 % gold. [8, ICMI, 2010]

Figure 7 displays a scheme of processes involved in cyanide leaching of gold ores.

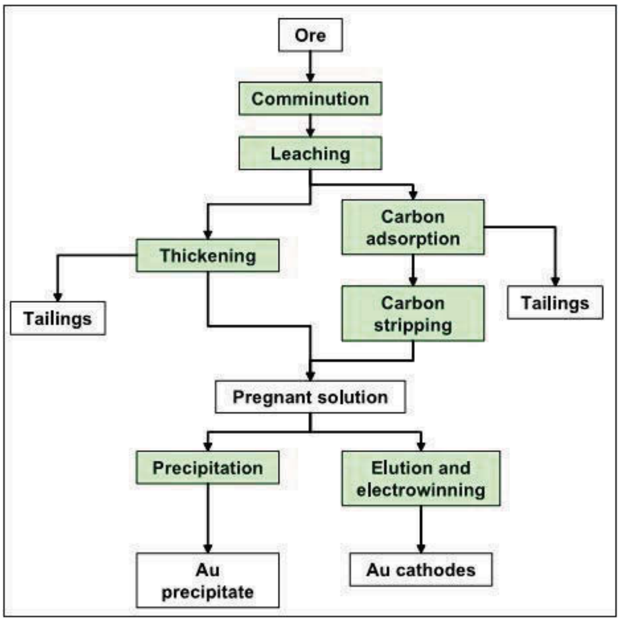

Fig 7: Processes involved in cyanide leaching of gold ores [9, European Commission, 2009, p.67]

According to [9, European Commission, 2009, p.462], tailings are defined as ore from which as much as feasible of the desired minerals have been removed, which accounts for solid heaps of spent ore and the slurry from tank leaching after the recovery of gold.

Refining

Refining comprises concentrating raw gold to obtain fine gold (commonly sold as 99.99 % or 99.999 % fineness of gold) by using **chlorination** (Miller-Process), **smelting** and **electrolysis** (Wohlwill-Electrolysis) [34, Antrekowitsch, 2010, p.22-24]

Waste management

The ultimate purpose of gold mining is to meet the demand for gold as a commodity on an economically viable basis [9, European Commission, 2009, p. ii]. The demand for gold has displayed a constant rise in the recent past (see subchapter 2.1.2 Global Gold Supply and Demand). At the same time, society – manifest in legislation and public opinion – has been demanding increasing consideration and care for the environment in industrial activity. As environmental management comes at the cost of economic success, this twofold requirement may seem like a contradiction in terms.

However, while responding to this requirement, the image of environmental management as an additionally imposed cost unit (albeit essential for receiving mining permits and public approval) may be replaced by a perspective of increased process efficiency. For example, the effort required for implementing strategies for reduced fresh reagent addition, such as computer-based process control [9, European Commission, 2009, pp. 358-359] and reagent recycling techniques, such as cyanide recovery by the Acidification-Volatilization-Recovery (AVR) process [11, USEPA, 1994, p.12] also results in reduced fresh reagent input, which reduces operational costs for two reasons: firstly, less reagent needs to be purchased and, secondly, the amount of reagent that needs to be treated at high cost prior to effluent discharge is decreased23).

As a consequence, the present state-of-the-art of gold extraction suggests an approach that combines the two interests for contemporary mining, in which economic success not only coincides with an environmentally sound operation, but is in fact conditioned by the latter.

In the context of waste management, it has become common practice to use the term "cradle-to-grave" to denote a particular kind of concept. This concept provides for the principle that the whole life-cycle of any activity or product is considered from the design stage ("cradle") right until the end ("grave") of the project. [9, European Commission, 2009, p.429]

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23) The sequence of these logically conditioned facts is reminiscent of the first basic principle of waste management of the Austrian Waste Management Act 2002, which requires "waste prevention" by keeping the quantities of waste to a minimum (cf. [35, BGBl., § 1 (2), 2002] in German or for a corresponding English translation [36, Lebensministerium, 2006]

Closure

A detailed plan for the site closure is already requested in application procedures for obtaining a mining permit. However, such a plan needs to be reviewed and up-dated throughout the whole life-cycle of a mine to ensure several issues [9, European Commission, 2009, p.328], including:

- Closure costs which are an integrated part of the assessment of options
- Premature closure has to be considered in the design of facilities
- After-care has to be minimized
- The design of closure options also includes risk assessment.

According to [9, European Commission, 2009, p.328], the land use after mining activities have ceased is a crucial aspect of any closure plan. Possible options for successive land use [9, European Commission, 2009, p.332] include:

- Natural recolonisation by local vegetation
- Commercial forestry
- Agriculture
- Other industrial activities
- Use of infrastructure built during the operational mine life by the region.

Recultivation

Recultivation is designed to mitigate above-ground disturbances and return the land to the local community for after use. [9, European Commission, 2009, p.364] recommended progressive restoration/revegetation, i.e. during the operational phase, if possible, with benefits including:

- Capital expenditure for recultivation costs is spread over a longer period of time.
- Closure activities become part of the operational everyday life.
- Implementation time of the final closure plan is shortened.
- Progressive restoration allows obtaining experiences with closure options.

It has been noted that progressive restoration requires a progressive land use of the site. In case of the entire area being claimed by the ongoing operational activities, this beneficial option has to be discounted [9, European Commission, 2009, p.364].

The ensuing chapter is dedicated to the unit operations that are of paramount environmental significance, providing an overview of crucial aspects of waste management and closure. This includes the origins and descriptions of methods to manage some of the most prominent waste fractions, tailings, waste-rock and cyanide-containing waste.

3 Management of Acid Rock Drainage, Tailings, Waste-Rock and Cyanide

In accordance with the scope of this Thesis the management of acid rock drainage (ARD), tailings, waste-rock and cyanide in gold mining is described from the point of view of the European standards.

The following chapter provides an overview of emissions to air in gold mining, a brief introduction to "best available techniques" (BAT) as the European standards and a discussion of the management of paramount waste issues related to gold mining.

Emissions to Air in Gold Mining

Out of the three environmental media: air, water and land (soil), which are generally acknowledged as subjects of consideration in environmental management, liquid and solid waste are paramount in gold mining, as far as quantity and severity of impact of waste is considered. That is why the main focus is laid on liquid and solid waste subsequent to a brief description of emissions to air.

Emissions to air, which include noise, dust and gases are less prominent [9, European Commission, 2009, p.34]. Effective equipment is available to reduce such emissions.

Noise emission can be reduced by minimizing truck traffic by replacement through conveyors. Housing of the latter may additionally contribute to a reduced noise level and also allows installing equipment for dust emission control. [9, European Commission, pp.34, 430, 2009]

Dust emissions mainly occur at the beaches of tailings ponds, the outer slopes of dams and heaps, the crushing unit of a processing plant and due to transportation. One technique to prevent dusting is binding dust by water, which is accomplished by wetting surfaces and installing scrubbers at crushers and conveyors. As a consequence, not only noise but also dust emissions may be reduced by implementation of conveyors, where applicable. [9, European Commission, 2009, p.viii]

In order to emphasize the mentioned principles two examples of gold mines in Sweden and Turkey are mentioned here. [9, European Commission, 2009, p. 217] reported that generated dust emissions were successfully controlled at the Bergama-Ovacik gold mine in Turkey by surface wetting of the roads and by a scrubber system at the crushers and conveyors.

As far as emissions of gases are concerned, volatilization of HCN gas may demand urgent management due to its high toxicity. [9, European Commission, 2009, p. 217] reported that at the Boliden (Sweden) mineral processing plant this necessity was met by a purification plant of process air which involved a wet scrubber to catch possible HCN gas. The process comprises HCN absorption in a sodium hydroxide (NaOH) solution which allows recycling some of the cyanide to the leaching plant. Both mentioned mines were reported to control HCN gas at the regeneration oven of the activated carbon by scrubbers as well.

3.1 Best Available Techniques (BAT)

In order to meet the challenges of environmental management, **the** European Commission has defined certain standards. In Article 2 (11) of the **Integrated Pollution Prevention and Control (IPPC) Directive** the term "best available techniques" (BAT) is defined as

> "the most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques for providing in principle the basis for emission limit values designed to prevent and, where that is not practicable, generally to reduce emissions and the impact on the environment as a whole" [37, European Union, 1996, Article 2 (11)].

The IPPC Directive furthermore specifies on the terms: "techniques", "available" and "best" as follows:

> << - "**techniques**" shall include both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned,
>
> - "**available**" techniques shall mean those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the Member State in question, as long as they are reasonably accessible to the operator,
>
> - "**best**" shall mean most effective in achieving a high general level of protection of the environment as a whole>>.

The European Commission furthermore appointed a Technical Working Group (TWG) which developed a Reference Document on Best Available Techniques (BAT) for Management of Tailings and Waste-Rock in Mining Activities between June 2001 and November 2003. The final version, which was published in January 2009, listed five iterative unit operations for the determination of BAT [9, European Commission, 2009, p. 427]:

(1) Identification of the main environmental, risk/safety issues for the assessed sector,
(2) Examination of the techniques to address those issues,
(3) Identification of the best environmental performance on the basis of worldwide data,

(4) Examination of the conditions for these performances, e.g. costs, cross-media effects,

(5) Selection of the "best available techniques" (BAT).

In addition to that, Annex IV of the IPPC Directive provides a list of aspects to be considered when determining BAT [37, European Union, 1996, Annex IV], such as:

- the use of low-waste technology;
- the use of less hazardous substances;
- the furthering of recovery and recycling of substances generated and used in the process and of waste, where appropriate;
- comparable processes, facilities or methods of operation which have been tried with success on an industrial scale;
- technological advances and changes in scientific knowledge and understanding;
- the nature, effects and volume of the emissions concerned;
- the commissioning dates for new or existing installations;
- the amount of time needed to introduce the "best available techniques";
- the consumption and nature of raw materials (including water) used in the process and their energy efficiency;
- the need to prevent or reduce to a minimum the overall impact of the emissions on the environment and the risks to it;
- the need to prevent accidents and to minimize the consequences for the environment;
- the information published by the Commission or by international organizations.

According to [9, European Commission, 2009, p. 428] there are three basic aspects of the BAT for tailings and waste-rock management which may be extended to BAT in general: **environmental performance, risk** and **economic viability**.

BAT were defined with the aim of establishing a reference for technologies that are most effective at for protecting the environment. That is why, environmental performance is quoted first. However, BAT do not only rely on one aspect alone, but comprise a balance of the three aspects inasmuch as risk and economic viability relate to the definition of "available” in BAT. As a consequence, a technology that takes into account only one of these aspects is automatically excluded from BAT, even if it performs better in that single aspect than BAT.

This interpretation of BAT also draws on Annex IV of the IPPC Directive [37, European Union, 1996, Annex IV] and [38, Kaiser, 2007, p.51] who pointed out the relation of costs and benefits for the environment in consideration of emission limit values.

While BAT are intended as a reference for a whole sector in order to allow the evaluation of a given environmental performance, BAT also recognize the need to assess every single solution site-specifically, taking into account each phase of an operation: design, construction, operation, closure and after-care.

BAT in Gold Leaching using Cyanide

According to [9, European Commission, 2009, p. 434] BAT requirements are specified for cyanide leaching of gold ores as the following:

- **Reduction of cyanide consumption**
- **Destruction of cyanide**
- **Application of safety measures**

Firstly, methods for the reduction of cyanide consumption such as minimizing cyanide addition, automatic cyanide control and peroxide pre-treatment of ore are described later in this chapter. Secondly, a variety of processes is available for the destruction of cyanide in order to meet the requirement of BAT to destroy remaining CN^{-}_{FREE} prior to discharge into ponds[24].

Furthermore, a holistic approach for the handling of cyanide is introduced in the course of this chapter (see subchapter 3.4.1 Holistic Handling of Cyanide as a Substance) which amends the possibility of reusing of cyanide by recycling methods to the measures required by BAT.

Thirdly, as far as safety measures are concerned, BAT require the cyanide destruction circuit to be designed with a capacity twice as large as the actual (operational) requirement. In response of the risk of pH dependent HCN formation (see section The Formation of Hydrocyanic Acid on p. 19), the addition of lime is commonly applied to control pH. Consequently, BAT demand a back-up system to ensure lime addition at all times. Finally, back-up power generators are required to ensure the power supply for the operation at all times.
[9, European Commission, 2009, p. 434]

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[24] According to [9, European Commission, 2009, p.442] no BAT emission limit values exist for cyanide concentrations in discharges into ponds for lack of an agreement in the TWG. Nonetheless, Directive 2006/21/EC on the management of waste from extractive industries demands in article 13.(6) cyanide concentrations at the point of discharge into the pond of 50 [mg/l] CN^{-}_{WAD} for facilities commissioned before 1 May 2008 and 10 [mg/l] CN^{-}_{WAD} for facilities commissioned after 1 May 2008. [39, European Union, 2006, Article 13.(6)]

3.2 Management of Acid Rock Drainage

[9, European Commission, 2009, p. 34] emphasized that the occurrence of acid rock drainage (ARD) was an issue related to mining, just as to gold extraction, of special environmental concern. Given that ARD is intensively related to both the management of tailings and the management of waste-rock, it is discussed beforehand in the following section.

According to [40, Thomé-Kozmiensky & Lorber, 2010, p. 10] the mobilization of metals from sulphide minerals by oxidation of the metal sulphides is referred to as acid rock drainage[25)] (ARD), or acid mine drainage (AMD). ARD can severely affect the quality of surface- and groundwater by causing impacts such as acidification and accumulation of metals (in plants and animals as well as sediments). As a consequence, species sensitive to elevated metal concentrations may be eliminated or harmfully affected. ARD may finally cause whole ecosystems to be destabilized. [9, European Commission, 2009, p. 37]

3.2.1 Background of Acid Rock Drainage

The formation of ARD mainly depends on the following mineralogical, physical and biological characteristics of the affected mineral. [9, European Commission, 2009, p. 36]:

- The presence of sulphide minerals;
- Oxygen availability;
- Bacterial activity;
- pH;
- Temperature.

Interactions between the characteristics (and the corresponding processes) may promote or inhibit the formation of ARD, which is determined by two contrariwise acting processes:

- The oxidation of sulphides;
- The dissolution of buffering materials (mainly calcite and alumino-silicates).

[25)] In compliance with the terminology used by [9, European Commission, 2009] the term acid rock drainage is used henceforth.

3.2.1.1 Acid generation

When metal sulphides are present in minerals (which is a common phenomenon in mining for Au, Pb, Zn, Cu, and other minerals, including coal [9, European Commission, 2009, p. 36]), the metal sulphides are oxidized when exposed to (atmospheric) oxygen and water, e.g. by the mining activity. In the first place, ARD is a problem because the oxidation of sulphide minerals produces free acid (i.e. H_2SO_4) which increases the solubility of dissolved metals and finally mobilizes them (cf. terminology of ARD according to [40, Thomé-Kozmiensky & Lorber, 2010, p. 10] on p. 36). Apart from the precondition of a present mineral sulphide source, the availability of oxygen as oxidant is considered the most important factor influencing ARD [9, European Commission, 2009, pp. 91-92].

Given that iron sulphides (pyrite FeS_2 and pyrrotite FeS) are the most commonly occurring sulphides and may also contain finely dispersed locked up gold, e.g. FeS_2 and FeAsS [38, Kaiser, 2007, p.60], the oxidation of FeS_2 is used to demonstrate the process. Equation [7] [40, Thomé-Kozmiensky & Lorber, 2010, p. 10] summarizes the chemical reactions which naturally take place in four steps, involving [41, Sarna, 2002, p. 5-6]:

(1) Oxidation of FeS_2 by oxygen and water

(2) Oxidation of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}) by oxygen

(3) Hydrolysis of Fe^{3+}

(4) Additional oxidation of FeS_2 by Fe^{3+}

$$4FeS_2 + 15O_2 + 14H_2O \rightarrow 4Fe(OH)_3 + 8SO_4^{2-} + 16H^+ \qquad [7]$$

Oxidation of sulphide minerals is a slow exothermal process. However, it may be significantly promoted by the activity of microorganisms like thiobacillus ferrooxidans. [41, Sarna, 2002, p. 7-8] reported that this strain of bacteria catalyzed the overall reaction at a factor of 10^6 by its metabolic activity which influences the first, the second and the fourth step involved in equation [7]. Furthermore, a low pH and elevated temperature are beneficial for the acidophilic and mesophilic bacteria involved in pyrite-oxidation.

3.2.1.2 Acid consumption

Apart from the paramount importance of oxygen, pH plays an important role as well. PH may impede or even prevent ARD at all by the dissolution of buffering materials, such as calcite and alumino-silicates. It is noted that the dissolution of calcite is a fast reaction which is assumed to consume acid at the same rate as acid is produced according to equation [7] whereas the dissolution of alumino-silicates takes place at a slow rate which cannot fully neutralize acid generation. [9, European Commission, 2009, pp. 91-92]

The overall reaction rate of sulphide oxidation may also depend on factors such as the type of sulphides, particle size and spatial variations inside of the mineral body. Smaller particle size corresponds to extended exposed surface area and may increase ARD proneness in tailings, as they are often finely ground by previous ore dressing. [9, European Commission, 2009, p. 36]

The spatial conditions within the affected mineral body influence drainage characteristics by factors such as precipitation of rain, infiltration rate, evaporation rate, oxygen mass transfer, compaction of the deposit and immobilization reactions (precipitation and adsorption) [9, European Commission, 2009, p. 38].

An overview of geochemical and physical processes (including their interaction) involved in the generation of ARD from mining waste is displayed in Figure 8. The formation of ARD is therefore prevalently dependent on three factors: the sulphide oxidation rate, the mobilization of metals and the water flow. [9, European Commission, 2009, p. 37]

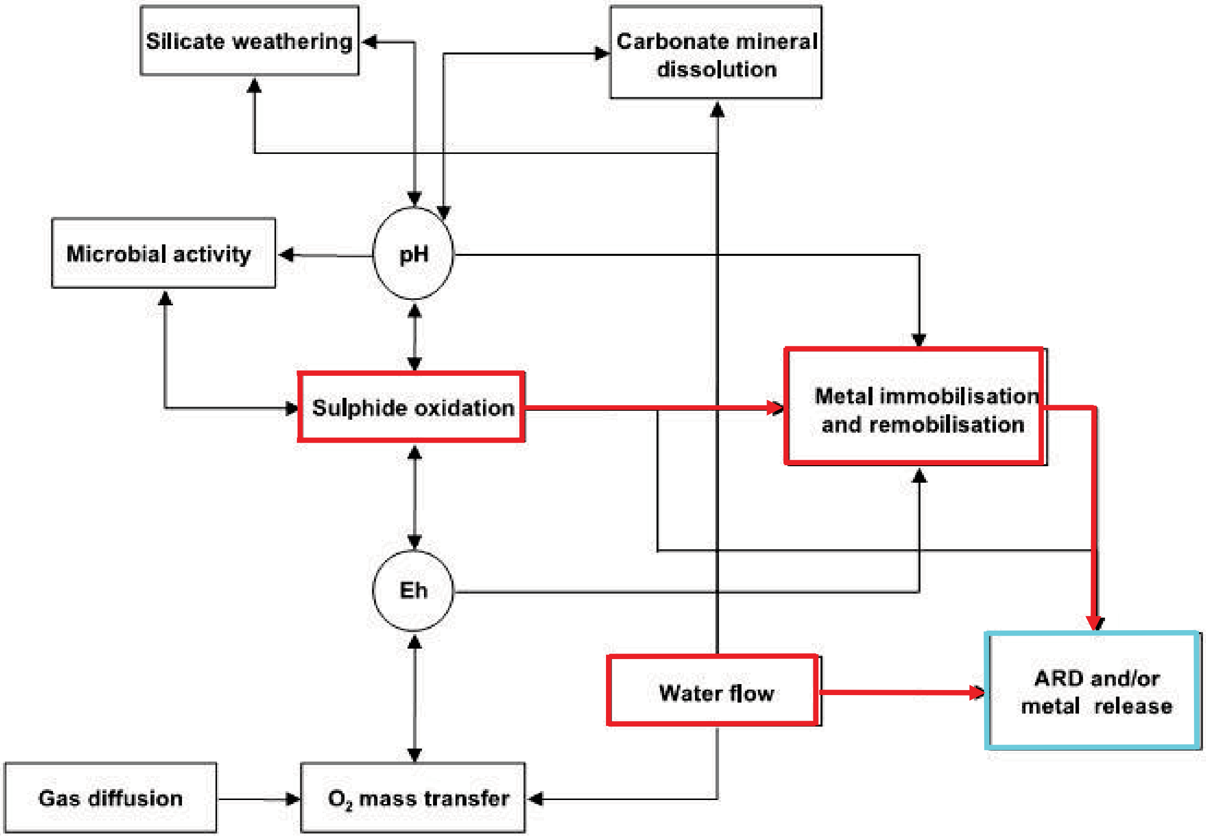

Fig 8: Paramount mechanisms and their interaction in ARD generation from mining waste, adapted from [9, European Commission, 2009, p. 37]

ARD can be generated any time from sulphide-bearing minerals under the described conditions [9, European Commission, 2009, p. 36]. However, only tailings and waste-rock management are considered in the present thesis.

3.2.2 Assessment of ARD Potential

The basis of ARD management is the investigation and consequent understanding of the characteristics of the affected material. Originally carried out as part of the risk assessment in the planning phase of the operation, all management is required to be reviewed and adapted in a cyclic way throughout and beyond mine life (cf. **cradle-to-grave concept**).

An understanding of the material allows identifying the need for preventive measures as a starting point of further action. In addition to that, an understanding of the material will also improve efficiency of applied measures. In this context the Concept of Selective Material Handling has become common practice, as will be described later on [9, European Commission, 2009, pp. 340-341].

ARD management comprises three **operation units**:

- **Assessment of ARD potential**;
- **Prevention of ARD**;
- **Control and Treatment of ARD**.

ARD management needs to assess whether the material will generate ARD or not. As described in subchapter Background of Acid Rock Drainage, the generation of ARD is governed by processes entailing acid generation and acid consumption. For estimation of the capacity of material to produce acid (i.e. Acid Potential AP) or consume acid (i.e. Neutralisation Potential NP) **Static Acid Base accounting tests** are commonly used. It should be noted that such tests are best applied as screening tools for fast results which requires eventually more detailed testing. [9, European Commission, 2009, p. 494]

Out of the variety of available tests [9, European Commission, 2009, p. 494] especially relies on the Acid-Base Accounting screening criteria recommended by the British Columbia Ministry of Employment and Investment of Canada. The provided guidelines stipulate the calculation of the Neutralisation Potential Ratio (NPR), which is the ratio of NP value to AP value (**NPR = NP : AP**). NP is to be determined by the "modified Acid Base Accounting procedure". AP is determined based on the sulphide sulphur content. The ARD potential is finally concluded according to Table 5. The guidelines indicate **likely ARD potential for NPR = NP : AP < 1:1 and no ARD potential for NPR = NP : AP > 4:1**. NPR values between one and four consequently provide an uncertain statement and require further kinetic testwork.

Table 5: ARD potential according to the Neutralisation Potential Ratio (NPR), adapted from [9, European Commission, 2009, p. 496]

ARD Potential	NPR	Comments
Likely	< 1:1	Likely ARD generating
Possibly	1:1-2:1	ARD if NP is insufficiently reactive or depleted fast
Low	2:1-4:1	ARD only if extremely reactive sulphides+NP low reactivity
None	> 4:1	More testing only if further decrease of alkalinity expected

3.2.3 Prevention of ARD

Prevention methods of ARD may be divided into short-term measures, which are used mainly during operation and long-term measures which are part of procedures referred to as decommissioning, closure and after-care of a mining operation. [9, European Commission, 2009, p. 92] stated that availability of oxygen was the most important factor which influenced the rate of sulphide oxidation. That is why the Prevention of ARD options subsequently described have one principle in common: to control and minimize the access of oxygen to the sulphide mineral. Prevention of ARD options are applied, according to viability, in management of both tailings and waste-rock.

3.2.3.1 Operational Short-term Prevention of ARD

Prevention of ARD is already an important issue during operation. Appropriate management has to take account of this fact already in the planning phase as well as during operation. Contrariwise, the costs for decommissioning, closure and after-care of a mining operation may be significantly higher.

In this context the **Concept of Selective Material Handling** may provide an effective tool for short-term Prevention of ARD.

The idea behind this concept may be described as separation of material in order to handle it in a more appropriate and hence efficient way. In Prevention of ARD separation is carried out according to the hazard which may emanate from the material, i.e. the potential of ARD generation. Separation provides two fractions, which are referred to as reactive and non-reactive material. Reactive material has to be treated. The costs of treatment are lower after selective material handling owing to the reduced amount of material in need of treatment. The non-reactive fraction is stored separately for facilitated access in case of potential future use. [9, European Commission, 2009, pp. 341, 353, 354]

Separation, as described in the Concept of Selective Material Handling, reminds of principles of waste management in the extractive industry (prevention or minimization, treatment, recovery, disposal), as required by Community Law [39, European Union, 2006].

The principles are implemented by methods such as re-use, recovery/recycling and – only as the final option – landfilling, which are based on separation of waste according to properties and hence future handling as well.

On the one hand separation of non ARD generating material may contribute to the overall revenue by including two of the mentioned principles: re-use and recycling. For example, heaps of (separated, non-reactive) ore which were leached and therefore considered tailings might be leached again at a later time (principle of re-use). In case of economic unfeasibility of this option the tailings might be used as construction material (principle of material recycling): on-site or even off-site, if sold.

On the other hand the Concept of Selective Material Handling in mining allows efficient handling or treatment of waste, e.g. in depyritisation. By separation of pyrite from liquid tailings, the "hazardous (part of) waste" – speaking in terms of waste management – may be treated accordingly, e.g. by subaqueous discharge [9, European Commission, 2009, p. 341].

The most important technique for separation of sulphides is flotation, which uses differences in wettability of material surfaces as separation property. According to the hydrophobic (water rejecting) or hydrophilic (water attracting) character of surfaces, particles will travel on froth to be removed by skimming the froth or sink down to be removed from the bottom of the flotation tank. Wettability can be chemically manipulated to enhance the wanted property and hence optimize flotation. For example, flotation using xanthates (flotation agents) and frothers (chemicals which enhance the stability of the froth, on which the particles may travel [9, European Commission, 2009, p. 63]) yields satisfactory results of pyrite recovery from siliceous tailings [9, European Commission, 2009, p. 353].

Within Prevention of ARD, flotation is used as a waste management method aiming at reducing the pyrite content. That is why the success of this method is primarily determined by the initial pyrite content (which needs to be removed). The main expenses are energy and reagent costs. As a parameter of control the pyrite content needs to be as low as to allow treatment methods to be successful (treatment methods include e.g. blending of wastes and liming, which are described later in section Treatment of ARD).

Pyrite recovery may be viewed as a further example of the two edged nature of selective material handling. On the one hand, the pyritic flotation product consists of concentrated, highly reactive matter which has to be disposed of. Consequently, disposal techniques have to be designed with care. Subaqueous disposal comprises a suitable option for reactive material of such kind, which is described in the section of long-term Prevention of ARD.

On the other hand, the pyrite concentrate may be used as sulphur source for the industrial production of sulphuric acid. [9, European Commission, 2009, p. 353] reports that the Boliden mill number one in Sweden sold a pyrite product until 1991.

Unfortunately, in recent years the market for pyrite has become very limited. As a consequence, the separation of FeS_2 in mining has decreased which has lead to a concentration of FeS_2 in the tailings in many cases which in turn increases the potential of generating ARD from the tailings.

3.2.3.2 Long-term Prevention of ARD Upon Closure

Long-term Prevention of ARD methods are based on the availability of water, at least in the form of moisture. Water has an oxygen diffusion coefficient that is 10,000 times lower and a saturated oxygen concentration that is 25,000 times lower than the one corresponding to air [9, European Commission, 2009, p. 349].

A cover of water as an oxygen diffusion barrier may be installed in two ways referred to as "**dry covers**" and "**wet covers**". Dry covers use low permeable layers (e.g. clay) with high water content (moisture) as oxygen diffusion barrier. A further option of a dry cover is to install an oxygen consuming cover: oxygen consumption by degradation of organic matter may contribute to keeping available oxygen low, similar to the buffering effect of the dissolution of calcite (which consumes acid and may counter ARD generation, see subchapter 3.2.1 Background of Acid Rock Drainage).

"Wet covers" feature a body of free water or – as a minimum – a water saturated cover. [9, European Commission, 2009, pp.341-342]

All dry cover options and one of the wet cover methods (wetland establishment) utilize, for enhancing their effect, the method of oxygen consumption by degradation of organic matter as a favourable side-effect of vegetating. [9, European Commission, 2009, pp.345, 352]

Dry covers

Dry covers are referred to as **cap-and-cover** solution which is also applied in the management of other wastes than tailings and waste-rock. A dry cover is composed of one ore more layers of different soil types (such as clay, silt, sand, gravel) which are arranged on top of each other, according to their specific properties and functions. The efficiency of a dry cover depends on sufficient moisture in the sealing layer, the total thickness of the cover (which may range between 0.3-3.0 m), the soil types used and the permeability of the sealing layer (with k-values commonly ranging between $1 \times 10^{-7} – 1 \times 10^{-9}$ m/s). [9, European Commission, 2009, p. 344].

As a minimum, a dry cover encompasses a protection layer. The liner may be further supported by a vegetation layer on top of the protection layer. The dry cover may be further supported by several other layers which have to be installed prior to the protection layer in order to lie underneath the protection layer.

Such additional layers may include a sealing layer, one or more drainage layers (which allows water control and also collection and treatment of seepage if needed) and a geotextile layer (normally made of high density polyethylene HDPE), as will be described further on.

The vegetation layer shelters the protection layer against erosion, growing grass on top of the protection layer [9, European Commission, 2009, p. 347].

The protection layer shelters the sealing layer from damage. The required thickness is dependent on local damage risks, including climatic and mechanical impacts, for example: erosion, frost action, drying, differential settlements, root penetration, digging animals and man-made intrusion [9, European Commission, 2009, p. 347]. In Europe, protection layers range from 0.5 m (under dry climatic conditions, such as in Aznalcóllar, Spain) and 1.5 m (e.g. in Kristineberg, Sweden), where the thickness of the protection layer was determined by frost [9, European Commission, 2009, pp.345-346].

The sealing layer fulfils two functions: firstly, it acts as an oxygen diffusion barrier by the essential high water content (moisture) within the sealing layer. Secondly, it impedes the infiltration to the material by its extremely low permeability. The diffusion rate of oxygen is dependent on the moisture content in a strongly non-linear manner. [9, European Commission, 2009, p. 345]

In principle, the cover is installed on solid ground as it may require the use of heavy machinery. That is why tailings ponds need to be dewatered and allowed to dry prior to the installation of a dry cover. In practice, however, this requirement is difficult to assure as much of the finer tailings remain soft and saturated. Another issue of concern may be dust emission during the drying period, which has to be countered by applying a dust control cover. [9, European Commission, 2009, p. 345]

The cap-and-cover method [9, European Commission, 2009, pp.344-345] has the purpose of:

- Impeding intrusion of oxygen from the surface into the tailings body;
- Impeding diffusion of oxygen within the tailings body ;
- Preventing ponding of surface run-off by grading the surface towards its edges (decline: 0.5 -1.0 %) and constructing by-pass ditches;
- Preventing the infiltration of surface water.

If the requirements for the cap-and-cover are met, both ARD generation and transport of reaction products are impeded.

The viability of dry covers also depends on qualified and readily available cover material. Considerable amounts of cover material could be provided by top soil from commencement of mining and non-reactive waste-rock from the extracting phase, if stored separately at the time of accumulation (cf. selective material handling in section Short-term Prevention of ARD on p. 40). If there is no waste material available, so-called borrow pits have to be excavated. Such borrow pits, evidently, entail a significantly increased footprint of the mining operation.

[9, European Commission, 2009, pp.345-348, 351] described four variations of dry covers which are displayed in Figure 9 and consequently named in increasing order of complexity: Type A, Type B, Type C and Type D. Type A covers are the simplest option of applying a dry soil cover. Type B, C and D covers are based on type A adding more features as required.

As indicated before, an oxygen consuming cover may form a fifth alternative which refines type B covers.

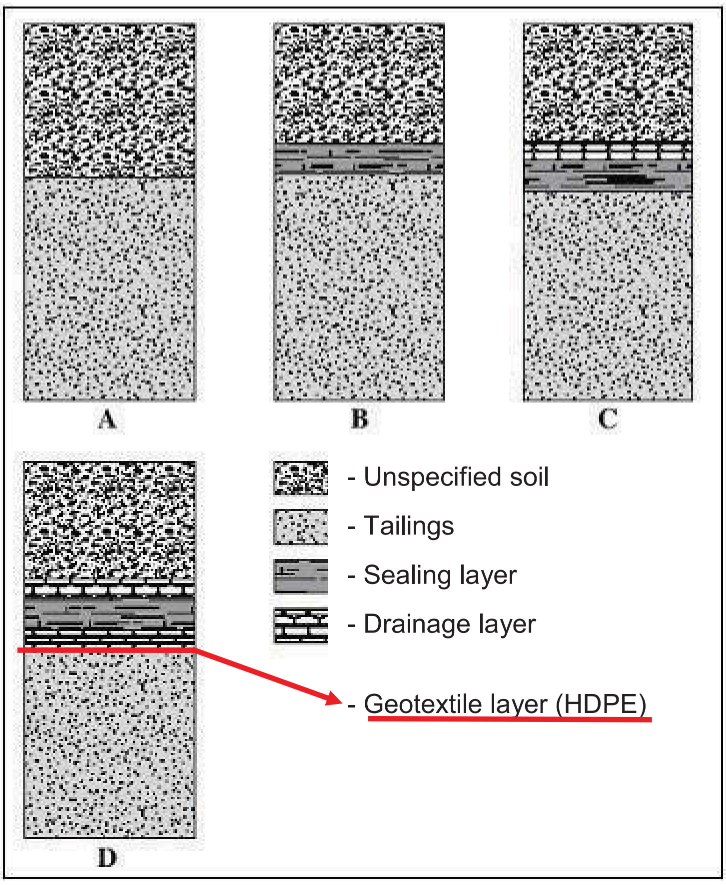

Fig 9: Four soil-cover designs, adapted from [9, European Commission, 2009, p.346]

- ***Type A Dry Covers***

In type A covers, the material to be covered (in this context tailings and waste-rock) is caped by unspecified and uncompacted soil material. Efficiency of this option is high as far as reduction of oxidation rate is concerned, yet poor in reduction of infiltration (for lack of compaction). [9, European Commission, 2009, p.345] reported that under Nordic conditions a layer of till (1.0-1.5 m in thickness) had achieved a reduction of oxidation rate of up to 90 % and had reduced infiltration by 10 %. Overall efficiency may be improved by applying the layer of soil material in several individually compacted layers.

- ***Type B Dry Covers***

Type B covers resemble the improved version of Type A (requesting a compacted sealing layer), but specify on the material, requesting low hydraulic conductivity material, such as clay. [9, European Commission, 2009, p.346] reported that in Kristineberg (Sweden) oxidation was estimated to have been reduced by > 99 % and water infiltration by > 95 % applying 0.5 m of compacted clay (as sealing layer) and 1.5 m of protective till.

Oxygen consuming covers may be classified as a special form of type B covers which both use a low permeable layer with a high water content as an oxygen diffusion barrier and a sealing layer. The permeable sealing layer contains organic matter and may be compacted. In some cases, also the protection layer may feature organic matter. During degradation of the organic matter oxygen is naturally consumed which decreases available oxygen for disadvantageous diffusion into the material. [9, European Commission, 2009, p.351]

[9, European Commission, 2009, p.351] reported that in Galgberget (Sweden) the tailings pond was covered by a mixture of fly ash and paper mill sludge as sealing layer and wood waste combined with coarse till as protection layer. The fly ash and paper mill sludge was compacted, according to the design rule for such layers and was installed in two layers for improved effect (cf. improved Type A above) with a total thickness of 1 m. The protection layer was designed for a total thickness of 0.5 m. [9, European Commission, 2009, p.351]

Follow up measurements showed that the design as laid out would promise satisfactory effects of several kinds. First and foremost a high degree of water saturation was indicated. The choice for fly ash as secondary material for the sealing layer entailed another benefit, as it raised pH by its content of calcium hydroxide ($Ca(OH)_2$). As a consequence, the pH dependant ARD generation process was suppressed (see subchapter 3.2.1 Background of Acid Rock Drainage). At the same time of suppressing acidophilic bacteria with a higher pH, metals would precipitate due to the cultivated H_2S production by sulphate-reducing bacteria. [9, European Commission, 2009, p.351]

It is noted, that the application of organic matter may also entail unfavourable dissolution of co-precipitated heavy metals, especially when brought into contact with iron hydroxides. [9, European Commission, 2009, p.351]

- ***Type C Dry Covers***

Type C covers add a drainage layer on top of the sealing layer. A drainage layer is a double-edged measure, however. The advantage of a drainage layer lies in the reduction of infiltration. Its disadvantage is that by draining water from the top cover it will deplete the sealing layer of (some) of its water content – i.e. its oxygen diffusion barrier – which may lead to an unfavourable increased transport of oxygen into the tailings. Therefore the necessity of a counterbalance has to be kept in mind when choosing a type C cover as a closure option by specific local conditions. [9, European Commission, 2009, p.346]

- ***Type D Dry Covers***

Type D covers introduce a coarse layer between the sealing layer and the tailings. Its function may be described as a capillary break layer, which on the one hand impedes dewatering by capillary transport downwards, and on the other hand impedes possible upwards transport of dissolved elements. The same problem of "drying/draining" the sealing layer applies just as with the drainage layer in type C. A geotextile layer is usually installed on top of the tailings (i.e. between tailings and the coarse layer) to avoid mixing of fines (tailings) with coarse fractions. [9, European Commission, 2009, p.346]

Wet Covers

Wet covers are efficient and cost effective methods to cover tailings ponds. In the literature wet covers are sometimes synonymously referred to as "water covers". In the scope of this Thesis, three methods are distinguished from each other, primarily by the depth of the water cover [9, European Commission, 2009, pp. 342, 343, 352], i.e.:

- **Water cover**
- **Wetland establishment**
- **Raised groundwater table**

As wet covers rely on significant amounts of **water as oxygen diffusion barrier**, a **positive water balance** is the most important precondition for successfully applying this method.

- ***Water Covers***

Water covers establish a water body on top of the material to be covered by **flooding the area**. In this context the flooding of tailings ponds is described, but the method could also be extended to other closure activities, e.g. flooding an open pit because of its ARD generating potential.

Owing to the physical properties of water (cf. low oxygen diffusion coefficient etc.) this method is highly effective. EC-BREF MTWR, 2009 reported that the water cover established on the Stekenjokk (Sweden) tailings ponds in 1991 had achieved values of effective oxygen flux through the water cover to the tailings of 1×10^{-10} kg O_2/m^2s, which is comparative to a dry cover solution. [9, European Commission, 2009, pp. 342, 343, 350, 352]

When taking a look on cost-efficiency the Stekenjokk project provides a clear statement in favour of water covers. The water cover solution was calculated to be six times more reasonable than comparable dry cover solutions. [9, European Commission, 2009, p. 343]

Bearing all these favourable features of a water cover in mind, proper planning will also consider the prerequisites and drawbacks of this method.

From the point of view of natural preconditions, the most important aspect, as already mentioned, is that water covers may be applied exclusively in areas of a positive water balance. [9, European Commission, 2009, p. 342]

The challenges from the engineering point of view include – as prominent issue – the long-term stability of dams, secondly a sufficient water depth in order to prevent re-suspension of tailings by wave action and thirdly long-term stable and sufficient discharge capacity. The water depth influences dam stability and discharge capacity, as more water exerts more pressure on the dams and capacity items (outlets, diversion channels, catch basins etc.). [9, European Commission, 2009, p. 342]

The concern of coping with the engineering challenges may suggest alternative solutions, which are described in the following section.

- ***Subaqueous Tailings Disposal***

Subaqueous tailings disposal means discharging tailings under water. It may be considered a sub-method of water covers which may be applied during operation. While [9, European Commission, 2009, p. 350] reported about tailings being disposed of into tailings ponds, flooded open pits, natural lakes and into the sea, it is noted that **in gold mining** subaqueous tailings disposal can **only** be applied by discharging **into tailings ponds** on account of remaining cyanide contents.

Subaqueous tailings disposal comprises an attractive option in management of reactive material. The advantages of this method [9, European Commission, 2009, pp. 349, 350] include:

- Effectiveness: The low oxygen diffusion and saturated oxygen concentration in water account for reduced availability of oxygen and hence little chemical activity related to ARD.
- Follow-up mechanisms[26)] support the disposal character of this method.
- Except for subaqueous tailings disposal into tailings ponds, no dams need to be built and maintained.
- Visual impression of the site is improved by a smaller footprint on land (no borrow pits need to be excavated, there is no need for a beach).

Aspects that may hinder the application of this method [9, European Commission, 2009, p. 350] include:

- Political issues, especially when applied to natural lakes and into the sea;
- Little knowledge of impacts on the subaqueous environment;
- Lack of space under water to contain the amount of designated tailings.

The costs for subaqueous tailings disposal are higher compared to conventional deposition during operation because of increased everyday adjustment effort. Significantly lower decommissioning costs may offset the beforehand incurred costs. [9, European Commission, 2009, p. 350]

- ***Wetland Establishment***

A wetland establishment comprises a further alternative of a wet cover e.g. when a water cover option would have been favoured yet had to be dismissed on accord of the risks related to the elevated water depth (dam stability). When establishing a wetland, **the area is flooded** just as with the conventional water cover method, save less water depth. A plant cover is installed instead which stabilises the bottom and prevents re-suspension of the tailings, taking over the function of a deep water body. Organic matter needs to be supplied in order to promote the growth of vegetation.

[26)] Low oxygen concentrations allow sulphate reducing bacterial activity which may also bind dissolved metals by sulphide precipitation, which is triggered by hydrogen sulphide. Chemical stability of the discharged material is further increased by a sediment layer which naturally covers tailings after cessation of active discharge on the bottom of the water body, additionally impeding interaction between the tailings and the water. [9, European Commission, 2009, p.349]

On the one hand this features another prerequisite to be fulfilled, but on the other hand the organic matter functions as oxygen consumption layer, as mentioned before. [9, European Commission, 2009, p. 352]

- ***Raised Groundwater Table***

The raised groundwater table method disclaims of an open pond altogether and emphasizes the advantage of missing risk related to dam construction and maintenance. Instead of that, water saturation of the tailings is assured by raising the groundwater table above the tailings level through mechanisms such as increased infiltration, reduced evaporation, increased flow resistance and capillary forces. A thin cover[27)], capable of the listed mechanisms, is applied and does not have to be compacted, meets low quality requirements and is not needed in abundant amounts. Such facts make the raised groundwater table method an attractive closure option when the following prerequisites are met [9, European Commission, 2009, p. 352]:

- **Positive water balance**
- **Groundwater table already close to the tailings level**
- **Careful groundwater modelling**

[9, European Commission, 2009, p. 352] stated that the raised groundwater table method comprised an "intermediate" solution, as far as the mechanism is concerned which is responsible for the oxygen diffusion barrier, namely water. A comparison of the three methods displays the wet cover, featuring a free water body, the raised groundwater table, featuring water saturated material and the dry cover solution, which needs least water in form of moisture within the sealing layer. The costs of the three methods follow this trend, i.e. **water covers are cheapest**, raised groundwater table solutions range in between and **dry covers are the most costly solution**.

3.2.4 Control and Treatment of ARD

Regular control of material with ARD potential is a matter of course in state-of-the-art mining. However, under certain conditions ARD generation cannot be prevented despite proper management (e.g. some operational conditions). In such cases the control of ARD migration is essential.

[27)] e.g. of simple soil, as used in the Boliden mining area (Sweden) [9, European Commission, 2009, p.211]

The transport of contaminants may be minimised by measures such as [9, European Commission, 2009, p. 354]:

- **Diversion of unaffected surface water**
- **Collection of affected surface water**
- **Control of groundwater flow**
- **Installation of simple covers to impede infiltration**

When ARD is generated it may be countered by adding **buffering material**. The source of such buffering material could be e.g. non-reactive tailings and waste-rock, given prior separate storage (cf. the Concept of Selective Material Handling on p. 40). In this case, the mixing of waste aiming at diluting the ARD producing material is referred to as **blending**. [9, European Commission, 2009, p. 354]

The addition of lime is referred to as **liming**. One option to provide lime to the ARD reactive material is to spread/apply limestone prior to installing a dry cover, which not only decreases ARD generation but also immobilizes possibly available ARD products. As of the amounts of limestone needed for effective buffering [40, Thomé-Kozmiensky & Lorber, p.16, 2010] recommended a minimum of 25kg/m^2 for a site in Bulgaria. It is noted that the buffering material should be locally available, most suitably consisting of waste material. Otherwise, transportation costs could impede the viability of this method.

Liming may also be applied to effluents in a treatment plant or directly at the discharge outlet which upon it is referred to as active treatment. In contrast passive treatment involves methods such as wetlands or anoxic limestone drains. [9, European Commission, 2009, p. 354]

3.3 Management of Tailings and Waste-Rock

The management of tailings and waste-rock provide one of the greatest challenges in the (waste) management of mining. Therefore, the purpose of tailings and waste-rock management is to deal with these two kinds of waste in an environmentally sound way.

According to [9, European Commission, 2009, p. 462] the term waste-rock refers to a part of the ore-body which cannot be mined and processed profitably for lack of existing ore. For the purposes of this Thesis, overburden material is included in the term waste-rock, which is generated during extraction.

Tailings consist of ore from which the desired minerals have been removed as much as feasible at a certain time [9, European Commission, 2009, p. 461]. Tailings from cyanidation are generated by two independent methods during processing, namely heap leaching and tank leaching. The choice of method depends on the grade of ore.

While in heap leaching tailings are generated in a coarse solid form (i.e. comprise of solid leached mineral which are sometimes referred to as spent ore as well), tank leaching generates tailings in a fine slurry[28)].

The characteristics of the material to be treated may have a significant on the choice of treatment method. That is why a brief description of some of the most important characteristics of tailings and waste-rock is provided before the actual treatment methods. As management methods for slurried tailings and waste-rock partly intertwine, they are described together.

Consequently, the ensuing section is divided into:

- Characteristics of materials in tailings and waste-rock;
- Management methods for solid tailings;
- Management methods for slurried tailings and waste-rock.

3.3.1 Characteristics of Materials in Tailings and Waste-Rock

As mentioned in subchapter Management of Acid Rock Drainage, ARD poses a serious problem. That is why the potential of tailings and waste-rock to generate ARD needs to be identified at an early stage of design as it determines the choice of methods downstream.

From a chemical point of view ARD-characteristics (see subchapter 3.2.2 Assessment of ARD Potential) and constituents of the slurried tailings from the CIP/CIL process, such as unreacted cyanide, metal complexes (e.g. as products from cyanide consumers), cyanate and thiocyanate need to be considered. [9, European Commission, 2009, p.203]

The management of tailings and waste-rock has to take into account physical aspects such as stability of the facility, capacity of the facility, retention time of substances etc. The mentioned aspects are highly interrelated with the physical and chemical characteristics of the material to be managed. In view of dam failures occurring ever and ever again[29)] not only in the gold mining industry – e.g. the recent dam failure at Ajkar-Kolontár (Hungary) on October 4, 2010 – the most prominent physical characteristics are listed as relevant to the stability of facilities. [9, European Commission, 2009, pp.70, 203]:

[28)] see Processing in the section Unit Operations of Gold Extraction

[29)] A chronology of global major tailings dam failures since 1960 can be reviewed online on: http://wise-uranium.org/mdaf.html [42]. More information on tailings and accidents related to tailings is available from http://www.tailings.info/accidents.htm

- Shear strength;
- Grain size distribution;
- Permeability;
- Porosity;
- Density;
- Solid to liquid ratio;
- Consolidation;
- Plasticity;
- Moisture content.

According to [9, European Commission, 2009, p.70] **shear strength** is the most important physical characteristic for the safe construction and maintenance of a heap or dam. On the one hand the importance is all the more emphasized as most of the deposited material is managed on heaps or in tailings ponds confined by dams and on the other hand the rest of the mentioned physical characteristics is related to shear strength.

Tailings characteristics may be significantly influenced (both physically and chemically) by mineral processing – see Table 6 which displays the examples of comminution and flotation – which in turn will have an impact on the tailings behaviour.

Table 6: Effects of selected unit operations from mineral processing on tailings characteristics, adapted from [9, European Commission, 2009, p.64]

Unit operation	**Tailings characteristics**								
	Grain size distribution	More fines	Specific surface	% solids	Reagents	pH	ARD influence	Surface properties	Particle shape
Com-minution	X	X(1)	X	X(2)	-	-	X	X	X
Flotation	-	-	-	X(3)	X(4)	X(5)	X	X	-

(1)… E.g. agitated mill generates more fines than ball mill
(2)… Crushing dry, tumbling mills and agitated mills
(3)… Flotation requires about 30-40 % solids, which means in practice water is added in most cases
(4)… Flotation reagents comprise collectors, frothers and regulators which are added selectively to improve separation
(5)… Flotation may raise or lower pH, depending on the applied reagents

3.3.2 Management Methods of Coarse Solid Tailings

[11, USEPA, 1994, p. 4] suggested two approaches for the treatment of tailings from heap leaching upon decommissioning:

(1) Natural degradation without any human intervention.

(2) Rinsing the heap followed by treatment of the rinse solution.

Although the second approach requires significant amounts of fresh water which has to be considered especially in areas with a negative water balance, the first approach is still less favourable from both an environmental and economical point of view. This claim is supported by the following two case studies.

Taking into account that tailings from heap leaching still contain considerable amounts of cyanide, the approach of relying entirely on natural degradation runs the risk of producing an abandoned site. [11, USEPA, 1994, p. 16] reported that a heap leach pad at the Hecla Mining Company's Yellow Pine Mine (USA), which contained 1.3 million tons of material, displayed an average cyanide concentration of 46.6 [mg/l] CN^{-}_{WAD}.

Economically speaking, natural degradation without any human intervention is not a sensible method, either. [11, USEPA, 1994, p. 7] reported about estimated treatment costs as being twelve times higher with the first method compared to the second one for a heap leach pad at the Snow Caps mine (USA). Estimates indicated that natural degradation in that case would have taken three years to achieve cyanide concentrations of 0.2 [mg/l] CN^{-}_{WAD} in liquid components, as demanded by the State of California at that time [11, USEPA, 1994, p. 28]. The estimated costs for security and maintenance accounted for 1,500,000 USD. Finally, the pad was treated using the **INCO SO_2-air Process** for 130 days, followed by 30 days of rinsing with fresh water at total costs of under 125,000 USD. That is why the method of natural degradation without any human intervention presents severe environmental and economical disadvantages.

There are two types of pads in use in heap leaching. In the case of permanent pads the ore is piled up once and (in principle) never removed. With on-off pad the spent ore is removed and replaced by fresh ore according to the leach cycle. As a consequence, this method requires an additional disposal area apart from the leaching pad and thus entails a greater footprint. In principal, the two types of pads are treated in the same way. However, with on-off pads the pad itself and the additional disposal area need to be decommissioned. [11, USEPA, 1994, p. 2]

Under certain circumstances, e.g. problems with the permeability of the heap or the need to use the pad otherwise, it may be required to dismantle the heap in order to separately treat the problematic part.

As treatment methods of tailings from heap leaching resemble operational schemes also the same equipment for application on the cyanide solution and the application of the rinsing liquid may be used. [11, USEPA, 1994, p. 4]

The second method comprises treating the tailings in-situ, i.e. rinsing the heaps with fresh water, which may be added with oxidizing chemicals for enhanced effect. The rinse solution is then treated by methods for cyanide destruction or cyanide recycling which will be described later. In order to reduce the consumption of fresh water, the treated rinse solution may be recycled to the sprinklers, establishing a closed water circuit. Rinsing is continued until desired (imposed) values for cyanide concentration (in many US states 0.2 [mg/l] $\text{CN}^{-}_{\text{WAD}}$, cf. [11, USEPA, 1994, pp.28-30]) are achieved in the rinse solution.

At closure the heaps are covered with locally available waste and sometimes vegetated which accounts for a dry cover of typ A (see section Dry Covers on p. 45).

ARD is not an issue with tailings from heap leaching as only oxidized ore is amenable to this method.

3.3.3 Management Methods of Fine Slurried Tailings and Waste-Rock

Management of slurried tailings that may be considered environmentally sound may be achieved by applying the methods displayed in the following two tables. In order to decide for the appropriate method, the ARD potential of the given slurried tailings needs to be assessed first.

ARD generating tailings may be either managed in a tailings pond applying subaqueous disposal techniques (to avoid contact with atmospheric oxygen, see subchapter 3.2.1 Background of Acid Rock Drainage) or may be backfilled underground. While tailings ponds need to be properly decommissioned at closure by applying a dry cover of type B, C, D or a wet cover, backfilling comprises an ultimate storage.

Tailings which are not prone to generating ARD may also be managed in tailings ponds or – after thickening – may be dumped on heaps or hillsides or also may be backfilled underground. Both heaps and hillsides need to be covered by a dry cover (in most cases a type A cover may be sufficient) upon closure.

Table 7 displays methods of disposal and Table 8 methods of material recycling of slurried tailings and waste-rock. In both tables characteristics are marked as "X" as specification applies and as "-" as specification does not apply.

Table 7: Methods of disposal of slurried tailings and waste-rock, adapted from [9, European Commission, 2009, p.70]

Method	Tailings	Waste-Rock	Comments
Discarding into ponds	X	-	As slurried tailings
Dumping on heaps or hillsides	X	X	Degree of dryness of tailings may vary significantly. Coarse tailings only
Subaqueous disposal	X	-	Into tailings ponds
Thickened tailings	X	-	Tailings need to be dewatered beforehand

Table 8: Methods of material recycling of tailings and waste-rock, adapted from [9, European Commission, 2009, p.70]

Method	Tailings	Waste-Rock	Comments
Backfilling	X	X	Used in underground mines and open pits
As product for land use	X	X	Tailings as aggregates, tailings and waste-rock as construction material for dams and roads

Discarding into ponds, dumping of coarse tailings and waste-rock on heaps or hillsides and backfilling of both tailings and waste-rock are the prominent methods for tailings and waste-rock management in selected gold producing mines[30)], as reported by [9, European Commission, 2009, pp.156, 205-212]. In accordance with the scope of this Thesis the focus is laid upon these methods.

3.3.3.1 Discarding of Slurried Tailings Into Ponds

Tailings ponds are artificially built surface structures which are confined by dams, forming a unit together which comprises one way of constructing a "tailings management facility" (TMF)[31)]. The main function of tailings ponds is to serve as a **safe temporary storage** of tailings during operation, whereupon sedimentation of tailings' solids takes place. Apart from sedimentation also treatment of tailings may take place, e.g. natural degradation of cyanide or precipitation of heavy metals [10, Needham, 2003, pp.17-19]. When tailings are not reclaimed for further treatment and the tailings pond is decommissioned it becomes an ultimate storage[32)]. [9, European Commission, 2009, p.71], [38, Kaiser, p. 28, 2007]

[30)] Bergama-Ovacik (Turkey), Boliden (Sweden), Orivesi (Finland) and Río Narcea (Spain)

[31)] The term TMF is used also in a broader sense, referring to additionally other techniques to manage tailings, such as backfilling and a tailings heap [9, European Commission, 2009, p.xliii]

[32)] The methods for decommissioning a TMF were described in section Long-term Prevention of ARD Upon Closure

The method of discarding tailings into ponds is usually applied for tailings from wet processing. The fraction of solids in ponds ranges from 20-40 % by weight. In most cases the solids sediment, forming two phases in the ponds: the solids of tailings on the bottom and a layer of free water on top of the tailings. [9, European Commission, 2009, p.71]

There are four concepts for arranging a tailings management facility (TMF), which are displayed in the following figures:

- Existing pit;
- Valley site;
- Off valley site;
- On flat land.

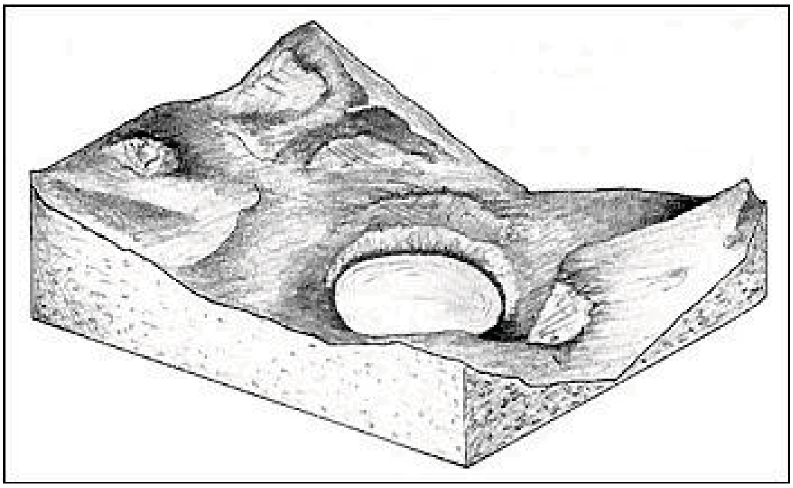

Fig 10: Tailings pond in an existing pit [9, European Commission, 2009, p.72]

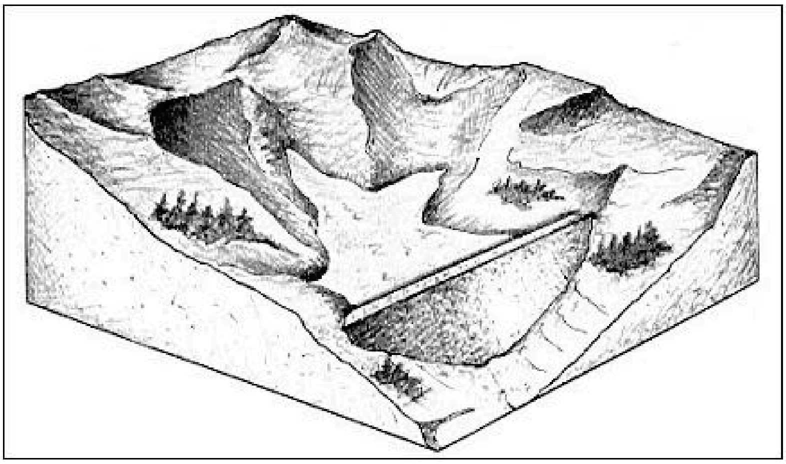

Fig 11: Tailings pond on a valley site [9, European Commission, 2009, p.72]

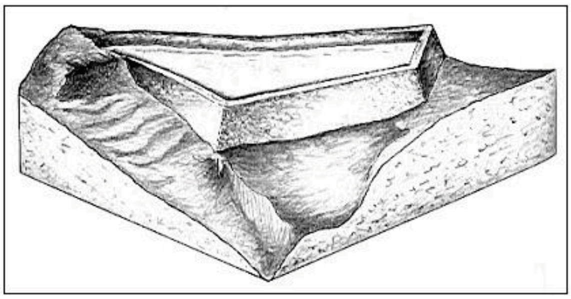

Fig 12: Off-Valley site tailings pond [9, European Commission, 2009, p.72]

Fig 13: Picture of a tailings pond built on flat land [9, European Commission, 2009, p.73]

For an environmentally sound operation of the TMF, several issues need to be taken into account already during the design phase, such as [9, European Commission, 2009, p.73], [38, Kaiser, 2007, p. 29]:

Concerning construction:

- The type of dam to confine the tailings;
- Diversion of natural run-off around or through the dam.

Concerning operation:

- Delivery of tailings;
- Deposition of tailings within the dam;
- Sedimentation behaviour of tailings;
- Management of free water;
- Protection of the surrounding area from environmental impacts;
- Monitoring systems in order to control the performance of the dam;
- Long-term issues related to closure and after-care.

When TMFs are designed, installed and operated according to BAT, TMFs provide controlled and safe containment of tailings. The ensuing section provides a brief overview of the most important concepts of constructing and raising tailings dams.

Confining dams

Confining dams are requested to fulfil three main needs. Firstly, they allow the control of the passage of water, secondly they have to resist the loads exerted by the tailings and the water and thirdly they are supposed to allow only seepage water to pass through, filtering solids in doing so. [9, European Commission, 2009, p.76]

Such requirements may be fulfilled when basic considerations are made, including: The ground underneath the dam needs to be prepared appropriately. If the groundwater table is on the same level or close to the base of the dam, a drainage system needs to be installed to avoid loss of stability. The required quality of the construction materials depends on the properties of the expected tailings and climatic conditions. Compaction of construction materials may also help to improve long-term stability. [38, Kaiser, 2007, p. 29]

According to [9, European Commission, 2009, p.74] dams consist of three main parts:

- The upstream section;
- The middle section or core;
- The downstream section.

The upstream section faces the tailings, i.e. it has direct contact with them. As a consequence, the material in this section needs to resist erosion (e.g. by wave action) and penetration, which is fulfilled e.g. by compacted sand. In contrast to the upstream section, the middle section– which is also referred to as core – needs to be permeable for seepage water. Infiltration needs to take place in a controlled way. Furthermore the core needs to resist mechanical impacts by e.g. rocks and must not become blocked by fine material. The downstream section remains dry at all times. When seepage is expected to be high, the downstream section may be kept dry by incorporating artificial membranes (filter cloths). [9, European Commission, 2009, p.74]

- ***Techniques to Construct and Raise Confining Dams***

According to [9, European Commission, 2009, pp. 75-80] there are four concepts to construct and raise confining dams:

- **Conventional dams**
- **The upstream method**
- **The downstream method**
- **The centreline method**

Conventional dams are dams which are built to their final height without the use of tailings as construction material and before tailings are deposited. This allows construction times to be comparatively short and the quality control for construction of the dam to be facilitated. As an additional benefit, supervision of the dam may be minimized during operation. [9, European Commission, 2009, pp. 75, 391, 392]

The main disadvantage of the renunciation of material recycling of tailings (as construction material) lies in the entailed considerable financial consequences. Construction materials need to be entirely provided by conventional means (e.g. borrow pits), unless non-reactive waste-rock is available. Further consequences comprise the increased area in need of closure management, probably including after-care. [9, European Commission, 2009, p.392]

A **"staged conventional dam"** may help to mitigate the high initial capital cost by constructing the dam as described above, with the exception that its final height is achieved in several construction phases, which will spread the costs over a longer period of time. [9, European Commission, 2009, p.73]

Summing up the characteristics of conventional dams it may be concluded that they are an expensive option for building a dam which may be chosen when:

- The site of the TMF is remote;
- Tailings cannot be used for dam construction;
- Free water needs to be confined in addition to tailings.

The need for the storage of free water could have several reasons, including a need of such water for plant use, a need for prolonged retention time of tailings water to allow natural degradation of toxic substances – such as cyanide – or the use of storage water for control of the water balance. [9, European Commission, 2009, p.391]

The storage of water by dams is subject to complying with conditions such as [9, European Commission, 2009, p.393]:

- Overtopping needs to be avoided;
- Sufficient capacity for emergency discharge (see section Management of Free Water on p. 63);
- Prevent liquefaction by keeping the toe of the dam unsaturated (e.g. by drainage);
- Monitoring the groundwater table.

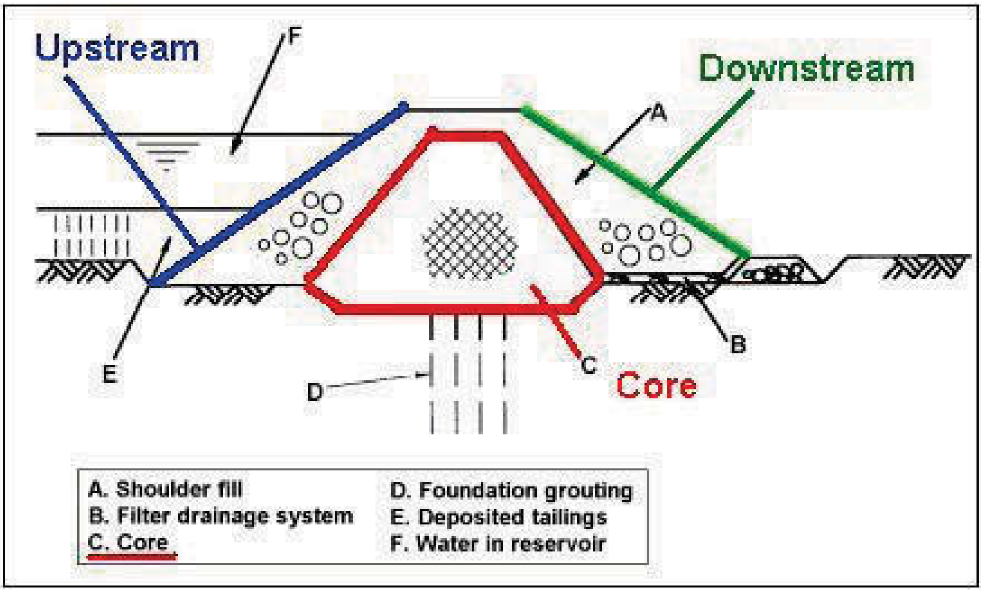

Fig 14: Schematic view of a conventional dam, adapted from [9, European Commission, 2009, p.75]

Figure 14 displays a schematic view of a conventional dam, indicating the three main constituent parts of a dam: **upstream section** (on the left shoulder), **core** (in the middle) and **downstream section** (on the right shoulder) [9, European Commission, 2009, p.75].

In contrast to conventional dams, the following three concepts of constructing a dam stipulate that construction of the dam is carried out in stages and coincides with the continuous deposition of tailings. As a consequence, **tailings may be used as construction material**. **Hydrocyclones** comprise an effective technique to obtain the coarse fraction of tailings from the hydrocyclone underflow for the dam raise. The fines (slimes) from the overflow are discharged into the pond, as can be seen in Figure 15. [9, European Commission, 2009, p.78]

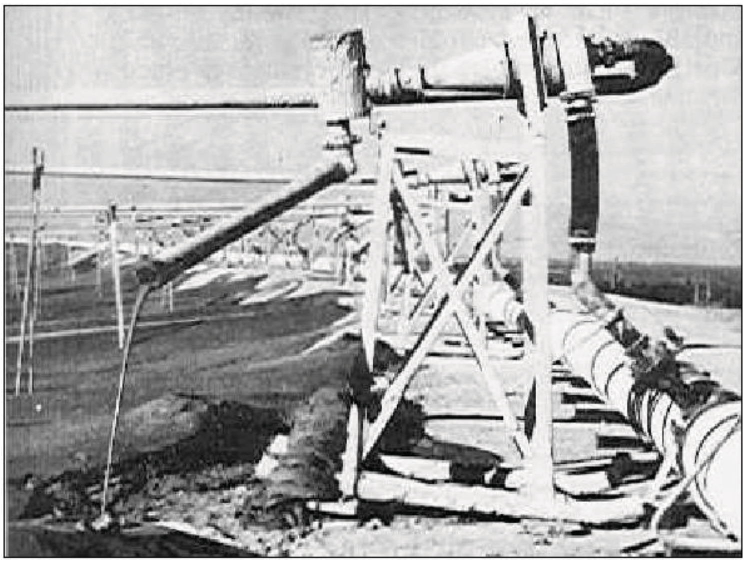

Fig 15: Size-Sorting of tailings by hydrocyclones [9, European Commission, 2009, p.77]

First, **the upstream method** requires the least amount of material related to a certain dam height which makes it the most cost-efficient method [9, European Commission, 2009, p.392]. However, the paramount disadvantage lies in comparatively low physical stability which makes the dams prone to liquefaction. Therefore, special attention needs to be paid to observing the groundwater table and taking precautionary measures by means of an effective drainage system. Figure 16 displays a schematic view of a dam raised by the upstream method using cycloned tailings. [9, European Commission, 2009, p.78]

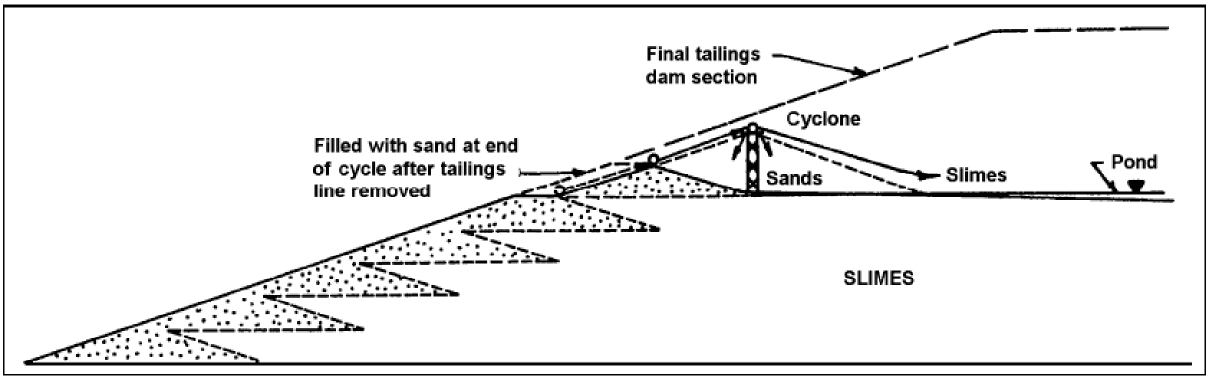

Fig 16: Construction of dams with the upstream method [9, European Commission, 2009, p.78]

Second, **the downstream method** is characterized by a more extensive need for material and area downstream (which increases the footprint). The composition of tailings allowing, i.e. if tailings possess a high coarse fraction, up to the entire structural portion may consist of tailings.

The **bank of hydrocyclones** is placed on the crest of the dam, discharging the coarse fraction downstream to form the dam. As a consequence the crest moves downstream which gave the method its name. Figure 17 displays a schematic view of a dam raised by the downstream method using cycloned tailings. [9, European Commission, 2009, p.79]

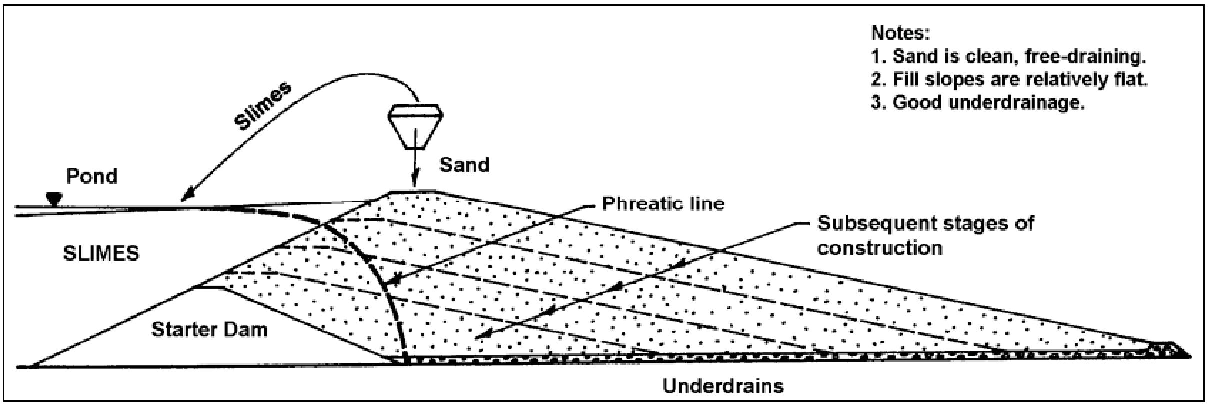

Fig 17: Construction of dams with the downstream method [9, European Commission, 2009, p.79]

Third, **<u>the centreline method</u>** offers a compromise between the high seismic risks of the upstream method (cf. the stability concerns mentioned before) and the material-driven costs of the downstream method. An additional factor in favour of the centreline method is the available surface area, which is not decreased with each dam raise, as illustrated in Figure 18. [9, European Commission, 2009, p.394]

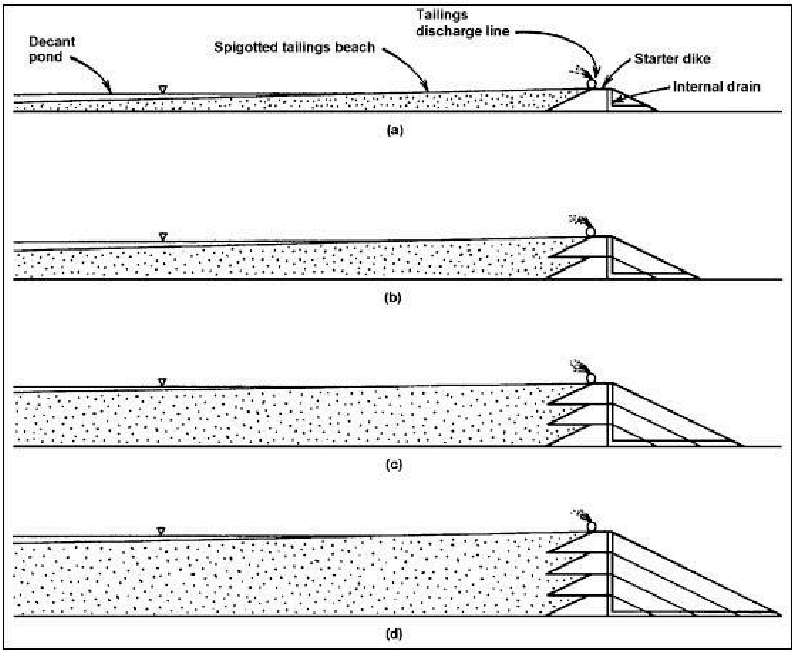

Fig 18: Construction of dams with the centreline method [9, European Commission, 2009, p.80]

- ***Management of Free Water***

The Management of free water is determined by two contradictory requirements. On the one hand, risk management requests the pond of free water to remain as small and shallow as possible. On the other hand, the pond requires free water to fulfil its purposes (cf. section storage of free water). A compromise between the two needs could be a **clarification pond** where sedimenting of fines and deterioration of toxic substances may take place apart from the actual dam. [9, European Commission, 2009, p.81]

Removal of free water primarily requires an adjustable outlet or a pump. The outlet comprises an extendible intake and a conduit to transport the discharge away. The intake may be designed in one of three ways: a decant tower, a decant chute or a pumped decant, as illustrated in the following figures. [9, European Commission, 2009, p.81]

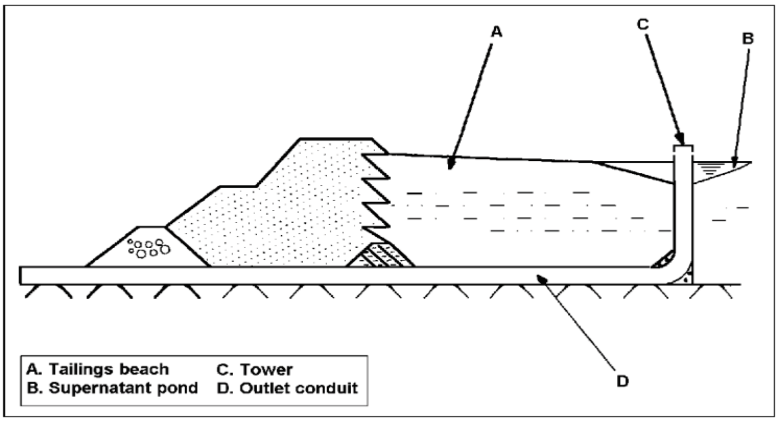

Fig 19: Tower decanting system [9, European Commission, 2009, p.82]

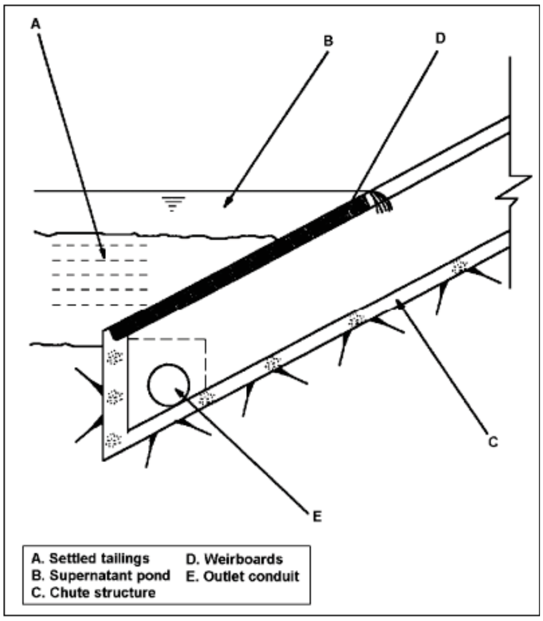

Fig 20: Chute decanting system [9, European Commission, 2009, p.82]

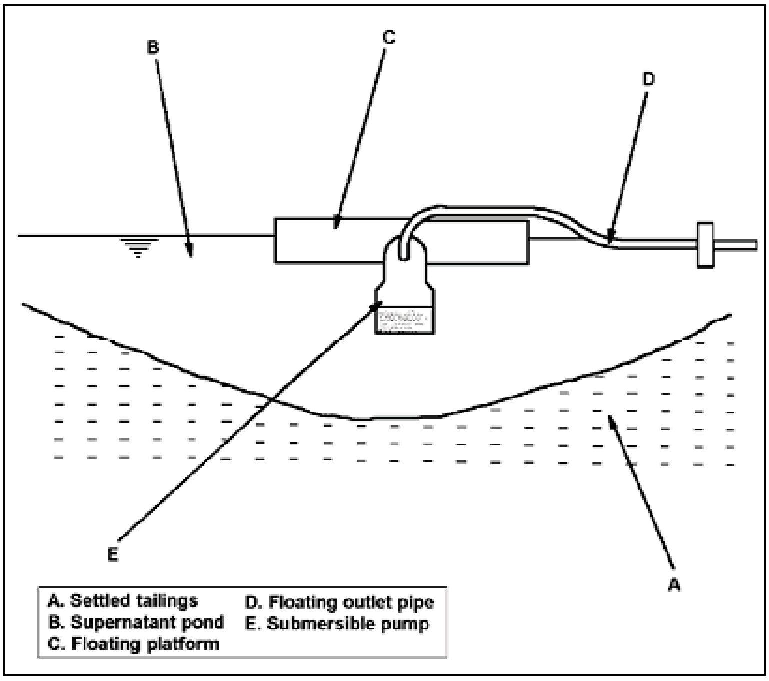

Fig 21: Pump barge [9, European Commission, 2009, p.83]

Emergency discharges are necessary in the case of extreme rainfall or snow smelt events to prevent over-topping which would lead to dam failure. In order to ensure that the emergency discharge takes place in a controlled manner, additional emergency outlets are incorporated in the design, usually in the form of large pipes intersecting through the dam. [9, European Commission, 2009, p.85] recommends designing the discharge capacity with a safety factor of 2.5. [9, European Commission, 2009, p.395]

3.3.3.2 Dumping of Tailings and Waste-Rock on Heaps or Hillsides

Dumping on heaps or hillsides is used in the case of both (coarse) tailings and waste-rock. When there is a potential of generating ARD, the ground needs to be prepared by a liner system which allows collecting, monitoring and hence treating of drainage. [9, European Commission, 2009, p.156]

Important factors to be considered in the design and operation of heaps are the heap stability and the properties of the supporting strata [9, European Commission, 2009, p.86]. Heap stability is increased autogenously by the coarseness of the material and also by the load exerted to the material during construction by spreading and compacting in thin layers and the use of heavy machinery. Surface run-off needs to be collected and assayed. If necessary the surface run-off is treated or discharged into the tailings pond. [9, European Commission, 2009, p.85]

3.3.3.3 Backfilling

The term backfilling is used specifically to denote the reinsertion of materials into mined-out parts which originate from the very site itself, whereas the insertion of material that does not come from the mining operation is termed infilling. Reasons for backfilling which is applied in underground mining as well as surface mining [9, European Commission, 2009, p.86], include:

- for underground mining
    - Ground stability;
    - Reduction of subsidence both underground and on the surface;
    - Provision of disposal capacity.
- for surface mining
    - Landscaping reasons;
    - Safety reasons (minimisation of risk of collapses).

In both concepts of mining, backfilling decreases above ground disturbance.

Backfilling is a widely applicable technique which is used for the disposal of both tailings and waste-rock, especially as a technique of ARD prevention. [9, European Commission, 2009, p.156]

Generally tailings need to be dewatered and/or mixed with structural products, e.g. cement. Backfilling exhibits a natural limit as of the amount of material which is possible to reinsert. The increase in volume by comminution entails that only up to 50 % of the tonnage extracted can be backfilled. The rest of the tailings and waste-rock needs to be managed by other methods. [9, European Commission, 2009, p.86] named four types of backfilling including **dry backfill, cemented backfill, hydraulic backfill** and **paste backfill**.

3.4 Management of Cyanide

For the purposes of this Thesis, the management of cyanide is described as the appropriate way of handling cyanide, in which the focus is placed on two aspects: Firstly, the primary objective of the management of cyanide is to protect the environment from severe negative impacts caused by the uncontrolled release of cyanide into the environment, which coincides with the primary objective of BAT. Secondly, appropriate handling of cyanide should be viewed from a holistic standpoint.

The history of abandoned sites and accidents related to the use of cyanide has proven that **precautionary environmental management is indispensable for state-of-the-art gold mining** on two accounts: First and foremost, the deterioration of the environment is extensive. [38, Kaiser, 2007, p.41] reported that the dam failure of Baia Mare (Romania) on January 30, 2000, released up to 100 t of cyanide at a concentration of 405 [mg/l] NaCN. After 72 km the plume of contamination still contained a concentration of 32,6 [mg/l] NaCN and showed concentrations above the emission limit values hundreds of kilometers downstream because of poor mixing and dilution. The accident resulted in extensive fish kills and deterioration of hydrobiology. Secondly, the costs for remediation exceed by far the costs for establishing and maintaining an effective environmental management.

[9, European Commission, 2009, p. 348] reported that the costs of remediation after the dam failure in Aznalcóllar (Spain) on April 25, 1998 amounted to the order of magnitude of EUR 33 million.

Due to the special properties of cyanide (i.e. toxicity, proneness to pH dependent volatilization, etc., see section The Formation of Hydrocyanic Acid on p. 19) cyanide-containing products require special attention not only during handling of products, but at every stage of their lifecycle. The awareness of involving production, delivery to the destination, handling within the operation to finally disposing of cyanide-containing wastes, features a holistic approach to the task which resembles the **cradle-to-grave concept** (mentioned in waste management). The following section describes the holistic approach to the management of cyanide relating to cyanide as an instrumental substance in gold extraction. Subsequently, the holistic approach is related to positive intervention by human stakeholders.

3.4.1 Holistic Handling of Cyanide as a Substance

Holistic handling of cyanide recognizes the use **of cyanide in gold extraction as the state-of-the-art**, dealing with cyanide in the following manner:

- Application, if and when absolutely necessary;
- Reduction of cyanide consumption, if and when possible;
- Recycling if and when possible and;
- Destruction (including natural degradation) in any case.

Necessary Application of Cyanide

There are various applications of cyanide in the mining industry. For the purposes of this Thesis, the most important application of cyanide is **leaching** which has been dealt with in section Processing.

Despite the predominant position of the application of cyanide, the last three possibilities of dealing with cyanide may help to significantly improve the environmental performance of an operation.

Reduction of cyanide consumption

Reduction of cyanide consumption may be achieved by measures including operational strategies [9, European Commission, 2009, pp. 358-359] and the use of alternative leaching technology, such as using bacteria for leaching gold from sulphide minerals (i.e. **"bioleaching"**).

There are several operational possibilities to minimize the addition of cyanide. For instance, a **control of water additions** to the circuit may help to keep the volume of water in the circuit to the necessary minimum providing two environmental advantages. Firstly, less volume of water means less need to add cyanide to maintain the appropriate concentration for leaching. Secondly, less operationally added water will also result in reduced loss of cyanide through the discharge of solution required for reasons of water balance.

An **automatic cyanide control system** offers a more sophisticated option for reducing cyanide, which might save up to 30 % of cyanide from avoided manual overdosing and up to 20 % of cyanide on account of higher sampling frequency, resulting in more accurate adjustment of cyanide addition. [9, European Commission, 2009, p.359] reported that the cost for such an automatic system amounted to approximately 100,000 EUR, requiring a cyanide consumption of 500 [t/a] NaCN to be economical.

As demonstrated by Elsner's equation [6] (see subchapter 2.2.4.5 Cyanidation — The Extraction of Gold with the Aid of Cyanide), the dissolution of gold by cyanide depends on oxygen. As a consequence, improving the supply of oxygen by **improved aeration**, adding elementary oxygen or applying pre-aeration of the ore by H_2O_2 will enhance the dissolution reaction.
Peroxide pre-treatment requires a profound mineralogical investigation of the ore and is reported to be applied to some sulphide ores.

While [10, Needham, 2003, p.7] reported that there was no comparable alternative to cyanide leaching in gold mining, [38, Kaiser, 2007, p.61] argued that **bioleaching** with the help of bacteria was a true alternative technology to cyanide leaching for the recovery of gold from sulphide minerals such as pyrite (FeS_2) and arsenopyrite (FeAsS).

In principle, **bioleaching** is determined by three main chemical reactions [38, Kaiser, 2007, p.60]. The bacteria act as a catalyst for the oxidation of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}) (cf. equation [8]) and the formation of sulphuric acid out of sulphur, oxygen and water (cf. equation [9]).

$$4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O \tag{8}$$

$$2S + 3O_2 + 2H_2O \rightarrow 2H_2SO_4 \tag{9}$$

Fe^{3+} will react with the sulphur bonded to the valuable mineral (demonstrated as M in equation [10]) forming Fe^{2+}, elementary sulphur and the valuable mineral.

$$MS + 2Fe^{3+} \rightarrow M^{2+} + 2Fe^{2+} + S \tag{10}$$

[38, Kaiser, 2007, p.60] supported his claim by reporting on **bioleaching** being used at an industrial scale in South Africa33), Brasil, Australia, Ghana, Peru, China and Kazakhstan. In fact, **bioleaching** can be considered as the wanted technological application of the unwanted ARD generation.

Recovery of Cyanide

Cyanide recovery offers another option for decreased cyanide consumption. Two completely different processes are described within this Thesis. While recycling of cyanide with the help of the **Acidification-Volatilization-Recovery (AVR)** process represents proven technology, the recycling of cyanide using membrane technology is still under development.

The AVR process is extensively described in the literature, e.g. by [11, USEPA, 1994, pp.12-14]. The process is based on the tendency of cyanide to volatilize as HCN at low pH. Hence, the pH of a cyanide solution to be treated (in most cases a barren solution) is lowered by addition of sulphuric acid. As a consequence, HCN gas is formed according to equation [11].

$$H^+(aq) + CN^-(aq) \rightarrow HCN(g) \tag{11}$$

The liquid stream is then stripped with air and the HCN-laden air absorbed in caustic soda according to equation [12].

$$HCN(g) + NaOH(aq) \rightarrow NaCN(aq) + H_2O \tag{12}$$

The sodium cyanide solution is returned to the leaching circuit. As a last step lime is added to the wastewater in order to precipitate heavy metals.

---

33) The first application of bioleaching on an industrial scale has been in use since 1980 at the Fairview Gold Mine in South Africa [38, Kaiser, 2007, p.58]

Despite its environmentally favourable approach of recovering cyanide for reuse, the AVR process was criticized in the literature on account of elevated costs, especially for **safety measures** to balance the risk of generating highly toxic HCN gas, a probable hesitating attitude in authorities towards approval of installation and lacking practicability for slurries [9, European Commission, 2009, p.383]. [9, European Commission, 2009, p.217] reported successful cyanide recovery also from ventilation air in the Boliden mine (Sweden). [11, USEPA, 1994, pp.12-14]

The **recycling of cyanide** using **membrane technology** comprises a hybrid system of combined membrane and electro-winning technologies. The process is designed to recover cyanide which is bound in stable metal-cyanide complexes as well as copper as a by-product.

A clear liquor is required which is obtained through the removal of solids. The membrane unit consequently concentrates the copper-cyanide complexes and, finally, a metal recovery unit deposits the copper by electrolysis and liberates a portion of the CN^{-}_{WAD} as CN^{-}_{FREE}. [9, European Commission, 2009, p.438] indicated the practicability as there are no limits on treatable CN^{-}_{WAD} concentrations and recommended the process in contrast to resin exchange, precipitation and acidification processes.

Destruction of Cyanide

Destruction of cyanide is referred to as **oxidation method** because the carbon and/or nitrogen atoms in the cyanide molecule undergo changes in oxidation state [25, Young, 2005, p.105].

According to [9, European Commission, 2009, p.383] the following processes are currently applied for the destruction of cyanide:

- **Natural degradation;**
- **Alkaline chlorination;**
- **H_2O_2 oxidation;**
- **SO_2/air-process;**
- **Biological treatment.**

[9, European Commission, 2009, p.383] reports that natural degradation is the most common method of cyanide destruction in the world, especially in sunny climates, such as South Africa.

Natural processes for cyanide degradation that are taken advantage of, primarily in TMF, include neutralization by atmospheric CO_2 absorption, HCN volatilization, metal cyanide complex dissociation and metal cyanide precipitation [9, European Commission, 2009, p.383]. In addition to that, cyanide may also be naturally degraded by **microbial generation of cyanate and ammonia**, hydrolysis in soils, anaerobic biodegradation, as mentioned in subchapter The Background of Gold Production [11, USEPA, 1994, p.17].

Chemical degradation of cyanide by strong oxidizing agents is applied for the **oxidation** by **sodium hypochlorite (NaOCl)**, the **SO_2/air process** and with the aid of **H_2O_2**.

Oxidation by NaOCl is a well known process which entails a couple of drawbacks, however. In the literature especially costs, the inability to remove iron [9, European Commission, 2009, p.383], the forming of toxic cyanogen chloride and the high salinization of the waste water [38, Kaiser, 2007, p.26] are criticized.

The **hydrogen peroxide (H_2O_2) process** oxidizes cyanide to cyanate in the presence of copper ion according to equation [13] USEPA, 1994 p.10]:

$$CN^- + H_2O_2 \rightarrow CNO^- + H_2O \qquad [13]$$

The cyanate ion hydrolyses, forming ammonium[34] and carbonate according to equation [14]:

$$CNO^- + 2H_2O \rightarrow NH_4^+ + CO_3^{2-} \qquad [14]$$

[11, USEPA, 1994 p.10] reports that this process is applied to different cyanide-containing waste waters. [38, Kaiser, 2007, p.27] points out that heavy metal ions catalyse the decomposition of H_2O_2, which is why [9, European Commission, 2009, p.383] excludes the application of the H_2O_2 process for slurries.

The oxidizing action of H_2O_2 may be supported by UV-radiation by forming OH-radicals from H_2O_2 which are strong oxidizing agents [38, Kaiser, 2007, p.27].

According to [9, European Commission, 2009, p.384], the SO_2/air-process (e.g. INCO-Process) is the preferred treatment method for cyanide destruction in Europe. In this process cyanide in solution is oxidized by sulphur dioxide (SO_2) to cyanate according to equation (15):

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[34] It is noted that ammonia (i.e. NH_3), which is formed from ammonium (NH_4^+) at higher pH-values, is toxic to fish which should be considered when opting for this process [11, USEPA, 1994, p.8]

$$CN^- + SO_2 + O_2 + H_2O \rightarrow CNO^- + H_2SO_4 \tag{15}$$

The formed sulphuric acid is neutralized with lime. Copper ions act as a catalyst for the reaction. However, copper contents in the gold ore will also increase cyanide consumption by binding cyanide in copper-cyanide complexes (which deprives the leaching solution of cyanide as a lixiviant). [9, European Commission, 2009, p.384]

3.4.2 Holistic Handling of Cyanide as Responsible Human Behaviour

The second aspect of the afore mentioned holistic approach encompasses dealing with the stakeholders of the use of cyanide, focussing especially on human interventions related to cyanide as the responsibility of stakeholders.

Cyanide accidents caused by human error may be avoided by forming a sense of responsibility and aquiring practical skills and experience through the **training** and **education of staff**. In principle, every person who comes into contact with cyanide (directly or indirectly) should be considered as part of the target audience for such training, especially staff involved in the production, the delivery and handling of cyanide at the operation itself.

Training should cover behaviour during operational everyday life and in case of accidents, as described in the **10 Commandments of "best practice cyanide management"** [10, Needham, 2003, p.13], which draw on the ICMC [8, ICMI, 2010] (see also subchapter 4.3.2 Comparison with Best Practice Cyanide Management).

4 The Kori Kollo Gold Mine

The Kori Kollo mine is situated in Bolivia in the department of Oruro, approximately 200 km southeast of the city of La Paz and approximately 40 km northwest of the city of Oruro, lying within the provinces of Saucari and Cercado. The name of the mine, Kori Kollo, is derived from the indigenous language Aymará and can be translated as "hill of gold". [4, Miller et al., 1997, p. 10]

This chapter provides an introduction to the mining operations at the Kori Kollo gold mine run by the Empresa Minera Inti Raymi S.A. (EMIRSA). It provides a historical overview of operations – including recent production figures and most recent news on the ongoing **environmental audit** of the Kori Kollo gold mine – the investigation of the **environmental performance from 1982 until 2003** and the subsequent comparison of the environmental performance with European and non-European standards.

4.1 Historical Overview of the Operations

The district of La Joya (Spanish for "The Jewel") has been known for its mineral resources prior to Spanish colonisation. The Kori Kollo hill was mined by the Spanish conquerors until the beginning of the 20th century. Bolivian miners followed, but abandoned their activities due to the properties of the local mineral, inhibiting economical feasibility. In 1930 a Dutch group picked up mining at the hills La Joya and Nueva Esperanza (Spanish for "New Hope") but withdrew in 1946 when the sulphide ores ceased to be economical with given technology. [1, Peró et al., 1992, pp. 1-2]

EMIRSA has been mining gold at the Kori Kollo mine in a surface mining operation since **1982** and continues to do so. NaCN has been used as leaching agent from the beginning, which comprised the first application of cyanidation in Bolivia on an industrial scale. [1, Peró et al., 1992, pp. 1-2]

The mining history shaped by EMIRSA can be divided in several phases. Table 9 provides an overview of the events, the technology applied, the name of the site, the period of time covered by each event and a rough estimation of the capacity in order to obtain a sense of the order of magnitude of the mine (including decommissioned and currently running parts). For the purposes of this Thesis the **environmental performance** of the mine during mining oxidized ores of the Kori Kollo hill (**1985-1992**) and of mining sulphide ores from the pit (**1992-2003**) were investigated.

Table 9: Chronology of mining-related activities by EMIRSA at the Kori Kollo mine [4, Miller et al., 1997, pp.11, 112, Appendix X p.2], [12, Lorax, 2000, pp.1-1, 1-2], [44, Arze, 2007], [47, Columba, 2007], [46, boliviaminera, 2010], [43, Columba, 2010].

Event	Technology applied	Site	Date	Cap.
Prospecting and Exploration	Drilling and sampling	Kori Kollo hill, operation Llallagua	1982-1985	Reserves 70,000,000 t
Mining of oxidized ores	Heap leaching (NaCN), Merrill-Crowe	Kori Kollo hill	1985-1992	1,100 tpd
Mining of sulphide ores	Agitated tanks (NaCN), CIL	Kori Kollo pit	1992-2003	21,000 tpd
Closure plan	Restoration concurrent to mining where possible, separated encapsulation of sulphide tailings, piling up of topsoil close to area of extraction	Kori Kollo hill, operation Llallagua	1995-today	n.d.a.
Mining of oxidized ores	Agitated tanks (NaCN), CIL	Operation Llallagua	Since 1997	n.d.a.
Re-leaching of oxidized tailings	Heap leaching (NaCN), CIL	San Andrés processing plant	1999-2002	n.d.a.
Investigation of sulphide ores	Biological oxidation	Llallagua hill	Not mined	n.a.
Environmental audit	n.d.a.	n.d.a.	Expected 2011	n.a.

n.d.a.… no data available
n.a.… not applicable
Cap.… capacity: Reserves in [t]; Mine capacity in tons-per-day [tpd], as of average capacity of mined ore throughout operational life of mine
CIL.… carbon-in-leach

The technology applied for **processing oxidized** ores at the Kori Kollo hill was **heap leaching** with a **sodium cyanide (NaCN)-solution**, followed by the **Merrill-Crowe-Process** [5, Miller et al., 1999, Appendix XIV, p.1] (see subchapter 2.2.5 Unit Operations of Gold Extraction). In 1985, mine production started with leaching on permanent pads at the processing plant of San Andrés. With rising capacity needs, the second processing plant named Chuquiña was installed in 1988, operating one on-off pad. [1, Peró et al., 1992, p.5]

The plant at the Kori Kollo mine achieved an average capacity of mining 1,100 tons-per-day [tpd] of oxidized ores, recovering a total of 6.6 t of gold at a cut-off gold of 2.04 [g /t] between 1985 and 1992 [43, Columba, 2010].

Heap leaching was continued until 1992, when the sulphide ores emerged beneath the oxidized ores. As a consequence, the processing technology was continuously adapted to agitated leaching tanks and consecutive carbon-in-leach (CIL) process-technology [12, Lorax, 2000, p.1-1].

In **1995** the closure plan went into force, starting with the dump of waste-rock from sulphide ores, while the pit was still in full operation [44, Arze, 2007]. By July, 2010 the total earthworks progress of the closure plan amounted to 56 %. [43, Columba, 2010]

In **1997** mining of four additional deposits of oxidized ores commenced, namely the Llallagua hill (name of the hill in the local indigenous language), Nueva Esperanza east, Nueva Esperanza west and La Barca (Spanish for "The Boat"), collectively referred to as operation [4, Llallagua Miller et al., 1997, p.11]. The mining of sulphide ores of Llallagua was investigated but never realized. [4, Miller et al., 1997, p.112], [43, Columba, 2010]

From **1999** until **2002** oxidized tailings of the San Andrés processing plant were leached again. The already piled up permanent heaps suggested the sprinkling of fresh cyanide solution upon the material, showing a grade of gold of 0.68 [g /t] and a final cut-off gold of 0.5 [g /t]. A total of 1.5 t of gold were additionally recovered by re-leaching of the tailings. The success of processing low-grade tailings encouraged the continuation with the oxidized ores of Llallagua at a cut-off gold of 0.4 [g /t] in the year 2000. [12, Lorax, 2000, p.1-2], [43, Columba, 2010]

When the beneficiation of sulphide ores of the Kori Kollo pit ceased to be economical in **2003**, 92 t of gold had been recovered by processing an average 21,000 [tpd] of ores at a cut-off gold of 1.79 [g /t] [43, Columba, 2010]. In **2003** the closure activities commenced for that part of the operation, including the pit and the TMF [44, Arze, 2007].

Recent History of the Korio Kollo Mine and estimated End of Lifetime

[2, Storm, 2010 reports three years of remaining lifetime for the Kori Kollo mine based on information from December 2008. Declining mine production from 2006 until 2009 supported that statement. With no estimates available for 2010, Storm reports mine production of gold at the Kori Kollo mine for 2006, 2007, 2008 and 2009 as of 4.0 [t], 2.8 [t], 2.7 [t] and 1.9 [t], respectively.

In **December 2009** an **environmental audit** of the Kori Kollo mine commenced which was appointed to PCA Ingenieros Consultores S.A. by the competent environmental authorities in response to over 800 complaints from the surrounding communities [45, P.C.A., 2010, p.1-1]. [46, Boliviaminera, 2010] reports that the first phase out of three dedicated to planning the audit was completed and the second phase had begun on August 16, 2010 which consisted of acquisition of data from affected communities, taking samples of water, soil, vegetation, wild animals and domestic animals for the duration of 75 days.

Given that the acquisition of data has not been completed, no intermediate data was available so far. Results are expected to be reported to the Bolivian Ministry of the Environment and Water in 2011.

4.2 Investigation of the Environmental Performance

The investigation of the environmental performance of the Kori Kollo gold mine provided the basis for comparing it to BAT in the first place. A supplementary comparison was achieved by drawing on the Australian standards of "best practice cyanide management" and on guidelines commissioned by the U.S. Environmental Protection Agency (USEPA). Both comparisons are given in the subchapter 4.3 Comparing the Environmental Performance to European and Non-European Standards.

The investigation was carried out according to the chronology of mining at the Kori Kollo gold mine, i.e. dealing first with the phase of mining oxidized ores and subsequently dealing with the phase of mining sulphide ores. With the focus on products of the mining activities – with special consideration of by-products with the potential of negative impacts on the environment – on the handling of water and on the handling of the mineral, the results of the investigation derived **crucial environmental aspects** of the mining activities to be discussed. Finally, the results of the investigation enabled making a brief statement on the strong criticism EMIRSA has been confronted with in the last decade.

4.2.1 Products and Residues Resulting from the Mining Activities

The gold recovery processes of the oxidized and the sulphide ores resulted in a precipitate from the pregnant solution and bars of doré (an alloy of gold and silver) as marketable goods, respectively. Apart from these economic products the activities at the Kori Kollo gold mine have resulted in a couple of by-products and residues, which demand attention from the environmental point of view.

In case of gold recovery from oxidized ores, the main leftovers of primary concern consist of **solid tailings** (the heaps of leached mineral), **waste-rock** and the spent **cyanide solution (CN^{-}-solution)**. Solid and hazardous waste of various other kinds was generated in small amounts. [47, Columba, 2007]

The most important by-products from the mining and metallurgical activities associated with the sulphide ores are the **slurried tailings**, **waste-rock**, the **spent CN^{-}-solution** and the **subterranean water** pumped from the pit. The amounts of generated solid and hazardous waste of other kind where also small in mining sulphide ores. [47, Columba, 2007]

Table 10 shows an overview of these environmental aspects of concern and the corresponding installations.

Table 10: Environmental aspects of concern at the Kori Kollo gold mine [47, Columba, 2007]

	Kind of ore	Aspect of concern	Installation
1	Oxidized ores	Leached mineral	Heaps
2	Oxidized ores	Waste-rock	Waste dumps
3	Oxidized ores	CN^--solution	Processing plants
4	Oxidized ores	Solid waste, other than mineral	Waste dumps
5	Oxidized ores	Hazardous waste	Waste dumps
6	Sulphide ores	Tailings	Tailings dam
7	Sulphide ores	Waste-rock	Waste dumps
8	Sulphide ores	CN^--solution	Processing plants
9	Sulphide ores	Subterranean water	Pit, evaporation ponds, wetlands
10	Sulphide ores	Solid waste, other than mineral	Waste dumps
11	Sulphide ores	Hazardous waste	Tailings dam

4.2.2 The Handling of Water and the Handling of the Minerals

Analyzing the given information (see 1.3 Methodology of Investigation) two main topics of environmental concern were elaborated: The handling of water (liquids) and the handling of the minerals (solids). The environmental performance of EMIRSA was investigated in this study by describing the path of these two key issues from their sources, through the operations to their final deposits or sinks, finally leading to the discussion of the environmental impacts of these sinks in detail.

It makes sense to divide the operations at the Kori Kollo gold mine into two major groups from a technical and also historical point of view. The investigation corresponds to the **mining** of **oxidized ores from 1982 until 1992** and consequently dealing with the **mining of sulphide ores** at the Kori Kollo hill **from 1992 until 2003**.

4.2.2.1 Mining of Oxidized Ores of the Kori Kollo Hill

The Kori Kollo hill used to be a hill rising up to about 120 m above ground level. It was characterized by a topping cap of about 40 m of oxidized ores, a transition zone of mixed oxidized and sulphide ores of 4-10 m and the veins of sulphide ores which were mined until 238 m below the ground level. Oxidized ores at the Kori Kollo hill were mined from 1982 until 1992 by EMIRSA. It has not been possible to obtain enough data on figures about the mining of oxidized ores. However, the limited data obtained already allow drawing preliminary conclusions for this investigation. [47, Columba, 2007]

The Path of Water During Mining of Oxidized Ores

The path of water is described using a model with input streams to the unit operations, the use of water within the operation and output streams leaving the unit operations.

On the input side there are two sources of water:

- **Precipitation on the area of the operation;**
- **Freshwater taken from the river Desaguadero.**

Water from precipitation was controlled by a collection system, in order to prevent flooding of the area [1, Peró et al., 1992, pp.8-9] on the one hand and making it accessible as process water, on the other hand. The rest of the need for process water was provided by freshwater pumped from the river Desaguadero [47, Columba, 2007].

Within the operation, water was mainly used in the leaching process. The CN^--solution was produced by dissolving solid NaCN in water until reaching a final concentration of 0.5 [g/l] CN^-. After leaching, the pregnant solution passed through the Merrill-Crowe-Process. As output of the Merrill-Crowe-Process, a product of dressed Au and Ag was precipitated, apart from a poor solution of NaCN. This solution was enriched with fresh NaCN to reach the required concentration of 0.5 [g/l] CN^-, allowing it to be sprinkled again upon fresh heaps of mineral and therefore closing the water circuit. Another use of process water at the operation consisted of measures for diminishing the emission of dust. [1, Peró et al. 1992, p.5]

All water used in the operation was recycled in a closed circuit. As a consequence, the only output-stream of water during the operation phase can be accounted to evaporation losses. When the operation shifted continuously from oxidized ores to sulphide ores in 1992, the process water was transferred to the plant for processing sulphide ores. [47, Columba, 2007]

The Path of the Minerals During Mining of Oxidized Ores

The path of the minerals is described from the Kori Kollo hill as the source of the minerals through its processing steps to the final deposition of tailings. The first step of mining comprised "selective blasting", i.e. taking samples of minerals before the blasting and consequently dividing that section of the deposit into ore and waste material. [47, Columba, 2007]

The minerals were set free in a second step by the use of explosives. A total of 4,000 [tpd] of ore and 5,000 [tpd] of waste-rock were mined during the phase of oxidized ores, the latter being directly transported to the waste dump. The third step consisted of gradually crushing the ore to its final size of 1 inch (2.54 cm), suitable for leaching. The crushed ore was then, in a fourth step, leached at the two processing plants named San Andrés and Chuquiña. At the older plant of San Andrés (established in 1985) eight permanent pads were installed, whereas the plant of Chuquiña commenced operation in 1988, working with an on-off pad.

The leaching parameters were the same in both plants. The minerals were piled up in heaps of 3 m of height and the CN^--solution was applied at a concentration of 0.5 [g/l] CN^- and a throughput[35] of $\overset{\oplus}{V} = 0.2$ [l/m^2/min] CN^-. By dosage of lime, a pH-value of 10.5-11.0 was assured. The leaching time depended on the grade of ore and amounted to 30-45 days. [1, Peró et al., 1992, p.5], [5, Miller et al., 1999, p.1], [12, Lorax, 2000, p.1-1]

After leaching, the heaps were washed with freshwater (fifth step). The tailings from the two plants were treated differently as far as their final deposition (sixth step) is concerned. Residues from the permanent pad were encapsulated using mainly clay and covered with vegetation, whereas the leached minerals from the on-off pad were taken to the waste dump after rinsing. The oxidized tailings were partly used as construction material. Figure 22 demonstrates the path of the minerals during mining of oxidized ores. The use of oxidised tailings as construction material is indicated by dotted arrows [1, Peró et al., 1992, p.6], [5, Miller et al., 1999, p.1]

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[35] Throughput $\overset{\oplus}{V}$, defined for the purposes of this Thesis as liter per squaremeter per minute [l/m^2/min]

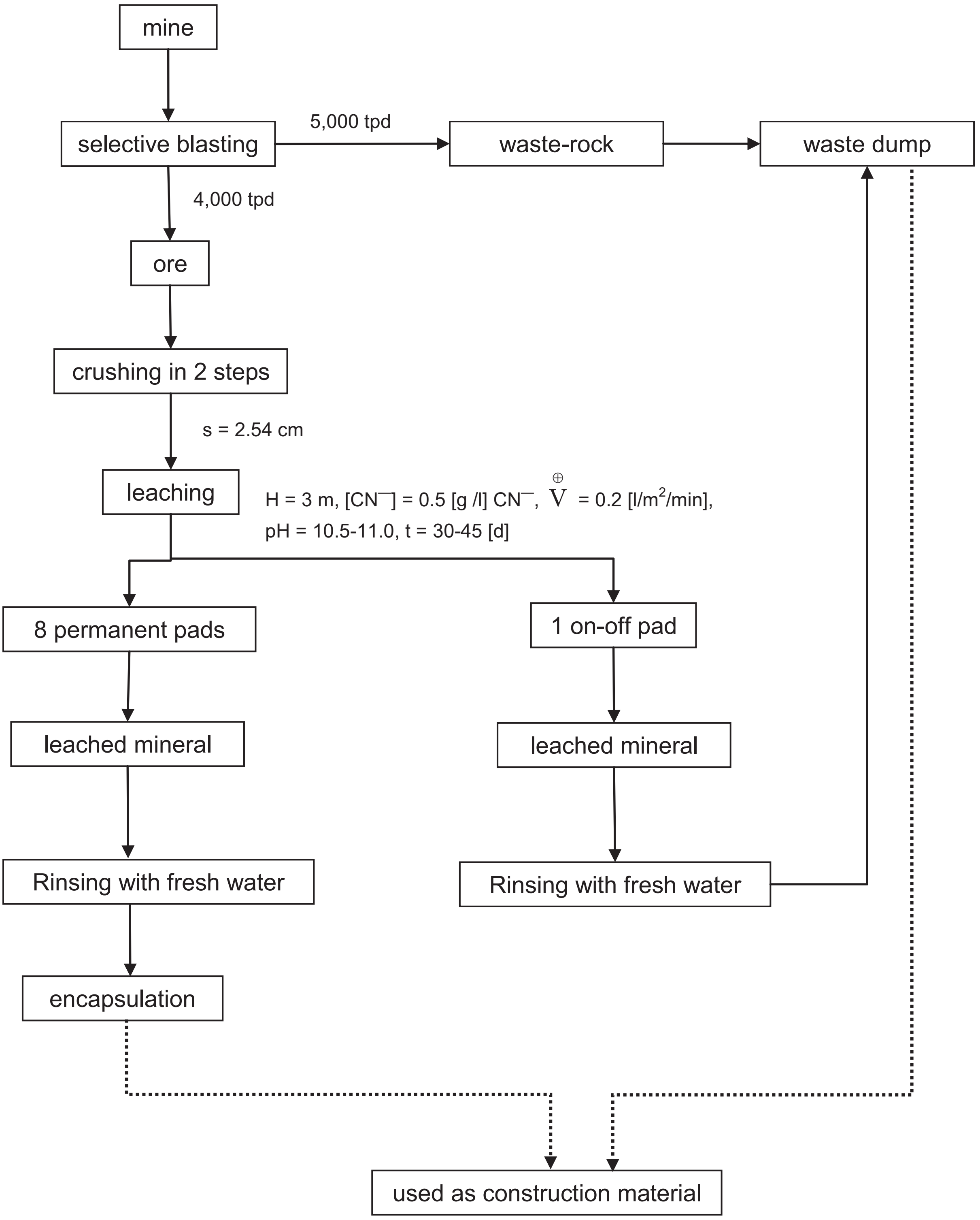

Fig 22: The path of the minerals during mining of oxidized ores [1, Peró et al., 1992, pp.5-6], [5, Miller et al., 1999, p.1], [12, Lorax, 2000, p.1-1]

4.2.2.2 Mining of Sulphide Ores of the Kori Kollo Hill

The phase of mining of sulphide ores of the Kori Kollo hill was carried out at the Kori Kollo gold mine from 1992 until 2003 as the seamless continuation of the first phase of oxidized ores. [47, Columba, 2007]

The Path of Water During Mining of Sulphide Ores

The path of water is described by input streams into the unit operations, the use of water within the operation and the process output streams. The last sink of water on the output-side consists of evaporation into the atmosphere and infiltration into the soil from the tailings pond and the ponds for collection of precipitation water. All figures in this section are merely indicatory to assess the magnitude of the material flow and should be taken as average values.

On the input side there are four sources of water:

- Precipitation on the area of the operation
- Freshwater taken from the river Desaguadero
- During the transition phase from oxidized ores to sulphide ores: Process water from the operation of oxidized ores
- Subterranean water pumped from the pit

Precipitation on the Area of the Operation

Precipitation on the area of the operation was controlled by a collection system feeding two natural ponds situated north of the tailings pond. There was no indication in the analyzed documents of a use of this water within the operation of sulphide ores. The water usually stagnated throughout the whole year. No more measures of control or treatment of that water were taken. [4, Miller et al., 1997, p.131].

Freshwater from the River Desaguadero

Roughly 6,700 m^3 per day (around 30 % of the plant's need) of freshwater were taken from the nearby river Desaguadero. This stream of freshwater was divided into two partial streams, as 3,900 [m^3/d] flowed directly into the breaking, milling and classification processes and 2,800 [m^3/d] were directed to the water treatment plant. On the one hand, this water of improved quality was used in the more sensitive parts of the operation, such as leaching, in the thickener and in the cyanide destruction plant. On the other hand, it was treated further on until reaching the quality of drinking water and was served to the workshops of maintenance, neighbouring villages and to other users. All used freshwater, be it of operational or domestic use, was finally disposed of into the tailings pond. [4, Miller et al. 1997, Annex V].

Process Water from the Operation of Oxidized Ores

As mentioned before, the process water from the operation plant of oxidized ores was transferred to the plant of sulphide ores as a measure of disposal.

Subterranean Water from the Pit

The most important aquifer of the Kori Kollo area lies 1-5 m below the surface. This circumstance made it necessary to continuously pump out subterranean water in order to allow the mining of the pit. The water was classified for its subsequent handling according to its total dissolved solids value (TDS) into four categories (cf. Table 11).

Table 11: Quality and handling of subterranean water, adapted from [4, Miller et al., 1997, p.116]

Category	TDS [mg/l]	Use/handling	Volume flow [m^3/d]
1	< 4,000	Plant	15,400
2	4,000-10,000	Wetlands	43,200
3	10,000-40,000	Evaporation pond phase I	
4	> 40,000	Evaporation pond phase II	

As can be seen in Table 11, the water pumped from the pit is characterized by very high TDS values. Since treatment was not economically possible, all water featuring TDS above 4,000 [mg/l] had to be disposed of by solar evaporation. Only category 1 water bearing TDS below 4,000 [mg/l] was used in the plant in the breaking, milling and classification processes. This amounted to 15,400 [m^3/d] and accounted for 70 % of the plant's water demand. That is why water pumped from the pit was considered as the main source of process water in the phase of sulphide ores. [4, Miller et al., 1997, p.116]

The Path of the Minerals During Mining of Sulphide Ores

The path of the minerals is described starting from the Kori Kollo hill as the source of the minerals, all the way through its processing steps to the final deposit of tailings. The first two steps of obtaining the sulphide minerals from the mine are methodically identical to the handling of oxidized ores ("selective blasting"). For a detailed description see section The Path of the Minerals During Mining of Oxidized Ores on p. 77.

For the following steps, average figures are provided from the Manifiesto Ambiental, Annex V water and mass balance [4, Miller et al. 1997, Annex V]. About 21,000 [tpd] of ore and considerable amounts (i.e. exact, reliable data was not available) of freshwater taken from the river Desaguadero were fed to the crushing unit (third step), producing a pulp of a grain size of 200 mm. At the milling and classification unit (fourth step), roughly 25 [tpd] of NaCN, a total of 27,000 [m^3/d] of water and 20 [tpd] of CaO-milk were added.

The resulting pulp, which was composed of 40 % of solids amounted to 46,000 [tpd] and was pumped to the leaching unit .

Leaching (fifth step) took place in agitated tanks, consuming 115,000 [m^3/d] of air and 800 [m^3/d] of oxygen. Adsorption (sixth step) required 27.5 [tpd] of activated carbon (of which 27 [tpd] were regenerated and recycled) and 86,000 [m^3/d] of air. The loaded activated carbon was separated from the pulp. From that moment onwards the pulp was considered to be tailings and was discharged into the tailings pond, whereas the loaded carbon was treated with an acid wash (seventh step). The acidity was managed by adding diluted HCl (3 %), which led to a consumption of 2.6 [tpd] of HCl.

Desorption (eighth step) was carried out with the aid of 50 [kgpd] of an inhibitor (i.e. M-40 O Nalco 9714), 425 [kgpd] of $NaCN$, 2.3 [tpd] of caustic soda and 10 [m^3/d] of water. This step resulted in inert carbon on the one hand which was used again for adsorption (at a rate of 70 % without treatment and 30 % being regenerated) and 1,700 [m^3/d] of a gold-laden rich solution, on the other hand. The latter was sent to electro recovery (ninth step). In a tenth step, the solution was filtrated, leaving behind a filtered solution which was recycled to the leaching step (fifth step) and a filter cake ready for smelting. In the last, the eleventh step, 113.5 [kgpd] of the final product, i.e. bars of doré, were cast at a rate of 23.54 % Au, 73.88 % Ag and 2.58 % of other impurities. Figure 23 illustrates the path of the minerals during mining of sulphide ores.

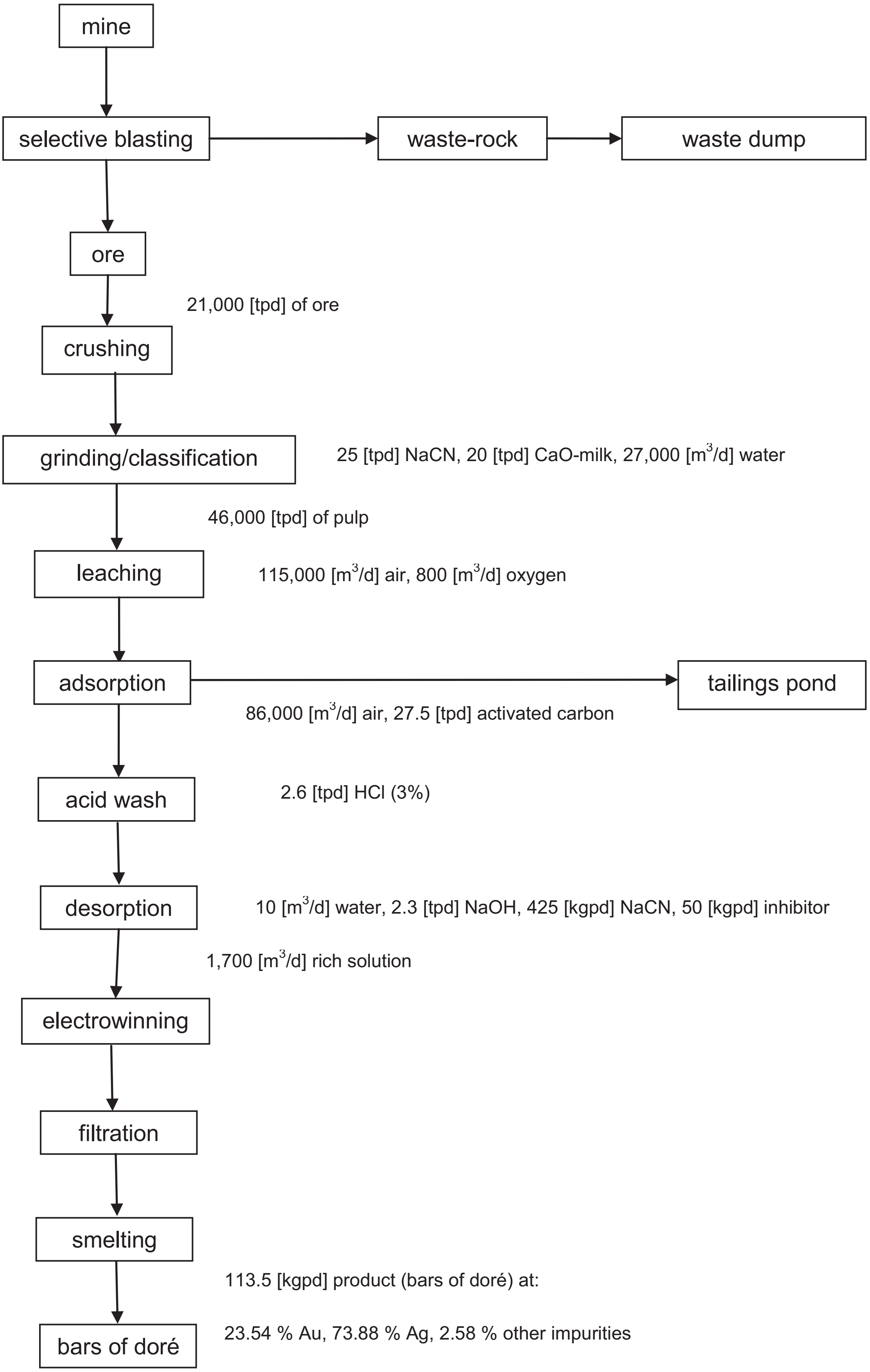

Fig 23: The path of the minerals during mining of sulphide ores

4.2.3 Environmental Aspects of Mining Oxidized Ores at Kori Kollo

The ensuing section is dedicated to the discussion of environmental aspects of mining oxidized ores at the Kori Kollo gold mine. The following aspects are discussed:

- Impacts from the mineral heaps: precipitation water leaching CN^{-} or other harmful substances.
- Handling of CN^{-}-solution: during operation and after the decommissioning of operation.
- Impacts from the waste dumps of oxidized ores.
- Points of doubt in EMIRSA's environmental performance.

Impacts from the Mineral Heaps

As mentioned before, precipitation water at the area of the gold mine was recollected and transferred into process water during operation. A possible contamination of this water due to water leaching the CN^{-} or other harmful substances from the heaps was incorporated into the closed circuit of water within the operation. Theoretically speaking, no water was enabled to seep into the ground, or reach the river of Desaguadero directly [47, Columba, 2007].

Handling of CN^{-}-solution

Cyanide is a toxic as well as expensive chemical and was handled with care at EMIRSA. In the case of spills, the area was treated with H_2O_2 or NaOCl for decontamination [47, Columba, 2007].

After the period of operation, the heaps were rinsed with water until reaching a satisfactory level of dilution of CN^{-} concentration. The **permissible limit** of CN^{-} content, according to national Bolivian law, is **0.2 [mg/l] CN^{-}** as of **CN^{-}_{FREE}** as a daily mean average value [48, MDSMA, 1995, p.200] which is congruent with e.g. U.S. legislation in Nevada [11, USEPA, 1994, p.29]. The cleansed mineral was then partly used as construction material or covered with soil and vegetation, according to the closure plan, whereas the process water was transferred to the plant of sulphide ores and was used again as such. [47, Columba, 2007].

Impacts from the Waste Dumps

The waste dumps constitute another environmental aspect. They resulted from depositing waste-rock and were encapsulated with lime and a cap of vegetation. Since oxidized mineral does not hold a potential of producing acid rock drainage (ARD), the only adverse impact that can be assigned to the waste dumps is of esthetical kind, as they alter the look of the landscape.

Summing up the information above, a generally environmentally conscious stance can be attested to EMIRSA from the theoretical point of view – i.e. based on existing written documentation. However, taking a closer look on the practical handling of environmental issues, **a few uncertainties** cannot be denied.

Points of Doubt in EMIRSA's Environmental Performance

[5, Miller et al., 1999, p. 2] states that the first heaps at the plant of San Andrés where partially piled up without previous preparation of the ground, such as compressing the soil, applying a liner of high-density polyethylene (HDPE), and a cover of lime on top of the liner etc., as indicated by the state-of-the-art nowadays. A liner was incorporated later at the plant of San Andrés. The younger plant of Chuquiña featured these precautionary installations from its beginning.

The possibility of measurable values of CN^- in samples taken from wells observing subterranean waters during the phase of oxidized ores is reported by [5, Miller et al., 1999, p. 2]. This was commented in the given document as **incidental infiltrations** neither affecting superficial waters, areas of agriculture or pasture nor subterranean waters currently in use. **No reports from a laboratory** were provided for this period of time to back up that statement.

[5, Miller et al., 1999, p. 2] reports that the ambient monitoring programme was continued during the next phase of sulphide ores and was intended to go on beyond the date of publication (January 1999). From December 1993 until December 1998, comparative laboratory results were obtained from sampling every six months within the area of San Andrés and Chuquiña by EMIRSA's own onsite-laboratory and also external institutions, the results of which were described to be featuring zero values of cyanide concentrations for nearly all of the investigated wells. [5, Miller et al., 1999, pp. 3-4] mentions that EMIRSA assigned SPECTROLAB, a laboratory from the Technical University of Oruro, and the National Institute of Occupational Health in Bolivia (INSO: Instituto Nacional de Salud Ocupacional) to provide **additional external control** during the ambient monitoring programme. INSO was cited of attesting no registered environmental impacts on the subjects of protection, which are air, soil and water, around the area of operation from 1985 until 1998.

Nevertheless, **two wells** within the ambient monitoring programme **displayed high values of CN^- concentrations** in the area of San Andrés. [5, Miller et al., 1999, p. 3] reports that the respective wells finally dried out, including those reporting some enhanced CN^- values.

The well PFSA-4 reported 0.88 [mg/l] CN^- in January 1994 and 0.52 [mg/l] CN^- in July 1994. This well provided no more data. At the next time of sampling in January 1995 it had been flooded. In July 1995 it had dried out and was marked as closed for the sampling in January 1996.

Although the well PFSA-4 served only twice for sampling and featured a declining tendency in the CN^- concentrations, **the reported values still should be taken seriously**, as they both **clearly exceeded the permissible limit of CN^- concentration**. [5, Miller et al., 1999, table 14.3-1]

The second well of concern was numbered PFSA-5. CN^- concentrations of **2.58 [mg/l] CN^-**, **4.88 [mg/l] CN^-** and **18.58 [mg/l] CN^-** were measured in **January 1994, July 1994** and **January 1995**, respectively. It also had dried out at the sampling period of July 1995 and was marked as closed for sampling in January 1996. This well is of particular interest, not only on account of higher CN^- values but also on account of its rising tendency in the CN^- concentrations and was already subject of external investigation [14, Montoya & Mendieta, 2006]. No reference was given on the characterization for CN^-_{FREE}, CN^-_{TOT} or CN^-_{WAD} when listing the two questionable wells in table 14.3-1 of the Manifiesto Ambiental. [5, Miller et al., 1999, table 14.3-1]

<u>As a consequence the following points of doubt can be singled out</u>:

(1) Values of CN^- being detected during the active period of oxidized ores:

Exact values were provided only from January 1994 onwards. What does "The possibility of measurable values of CN^-" for the period of 1982-1992 mean? Were the values just above the detection level or higher? Was the **permissible limit of 0.2 [mg/l] CN^-** as of CN^-_{FREE} as a daily mean average value being met or exceeded?

(2) Infiltrations not affecting waters and areas of current use:

Apart from mining, the area depends on agriculture and livestock breeding as economical activities [4, Miller et al. 1997, p.92]. Taking into account the negative water balance of the Bolivian Altiplano (Bolivian highlands), it does not seem prudent or responsible from a long term perspective to merely consider present-day uses of waters and areas, neglecting successive land use.

(3) High values of CN^- in two wells:

- Why did the two wells PFSA-4 and PFSA-5 dry out?
- What measures were taken by EMIRSA upon the detection of high CN^- values, e.g. increasing sampling rate by taking more samples at shorter intervals, searching for and finding the source of high CN^- concentrations and initiating remediation, etc.? There is no indication of EMIRSA having taken measures concerning that issue. EMIRSA stated there were no negative environmental impacts on waters, soil or the atmosphere due to the metallurgical processes of the enterprise [47, Columba, 2007], [4, Miller et al. 1999, p.238D], **contradicting** its own reports [5, Miller et al., 1999, pp.2-4]. When confronted with this evidence, EMIRSA staff answered evasively and unsatisfactorily [47, Columba 2007].
- Did EMIRSA report the high values of CN^- concentration to the competent authorities?

- In the case of EMIRSA reporting to national authorities: how did the authorities react? Relevant legislation exists and has been in force since 1995 [48, MDSMA, 1995]. However, **doubts remain as far as the implementation and execution of legislation is concerned**.

4.2.4 Environmental Aspects of Mining Sulphide Ores at Kori Kollo

The ensuing section is dedicated to the discussion of environmental aspects of mining sulphide ores at the Kori Kollo gold mine. The following aspects are discussed:

(1) Impacts from the waste dumps of sulphide ores;

(2) Salinization of soil due to heavy rainfalls;

(3) Contamination with heavy metals;

(4) Lack of information for ambient air monitoring.

Impacts from the Waste Dumps

Sulphide minerals in direct contact with the atmosphere are prone to produce acid rock drainage (ARD). Excavated un-mined minerals of the pit as well as material piled up as waste-rock on waste dumps are susceptible to this phenomenon. As mentioned before, ARD may cause severe problems by mobilizing and consequently releasing heavy metals to the environment.

Potential contamination of the environment by ARD was countered by encapsulation and constant monitoring. No evidence of leaking ARD was found after investigating the available information. The esthetical impact on the countryside remains, as it does with the waste dumps of oxidized mineral.

Heavy Rainfalls Supposedly Causing Salinization and Contamination of Soil with Heavy Metals

Approximately 43,000 [m^3/d] of water with a high TDS were pumped from the pit and had to be disposed of in evaporation ponds and wetlands. [14, Montoya & Mendieta, 2006, p. 51] reports over-topping of water from evaporation ponds after heavy rainfalls in the years 1999-2003 which supposedly contaminated the surrounding area. Furthermore, incomprehensible irregularities on concentration ranges of heavy metals in laboratory reports cited by EMIRSA are criticized by the same authors [14, Montoya & Mendieta, 2006, p. 170]

In 1997, the environmental monitoring programme was extended to include additional measurements of ambient air. Sampling took place at three sites, including one at the plant (primary sampling station), one before and one after (discharging canal) the area of operation. Two parameters were examined: the total suspended particles value (TSP) and PM-10. [4, Miller et al., 1997, p. 229]

<u>Consequently, the following points of doubt can be recorded</u>:

(1) EMIRSA denied any contamination caused by salinization and/or precipitation of heavy metals [47, Columba, 2007]. [14, Montoya & Mendieta, 2006, pp. 51-54, 170] severely **contradicts** this statement. As a consequence, this subject remains unacknowledged and requires further independent investigation to settle this issue (e.g. by the environmental audit currently carried out).

(2) The monitoring of ambient air quality suffers from lack of information. Due to the special properties of dust not only the quantity (TSP) and the size (PM-10) of the particulate, but also the shape of particles and **chemical composition of dust** need to be taken into account in order to judge the hazardous potential of dust.

4.3 Comparing the Environmental Performance with European and Non-European Standards

In light of the severe accusations that have been raised against EMIRSA, specifically against the environmental performance of the Kori Kollo gold mine, a comparison to European and non-European standards of environmental performance should allow for a judgemental assessment of the actual situation. These accusations include more than 800 complaints from surrounding communities [45, P.C.A., 2010, p.1-1] as well as scientific publications, e.g. [14, Montoya & Mendieta, 2006], and warrant a more systematic approach. This is achieved by drawing on BAT defined by the European Commission and the Australian standards of "best practice cyanide management" as well as guidelines commissioned by the U.S. Environmental Protection Agency (USEPA).

Among the **strongest points of criticism** that have to be made against EMIRSA are the **significantly elevated cyanide values of cyanide concentrations in two monitoring wells**. These are pointed out by [14, Montaya & Mendieta, 2006, pp.40-41] and could be verified by EMIRSA's Manifiesto Ambiental [5, Miller et al., 1999, table 14.3-1]. While this contamination of ground water is not in violation of any specific BAT norms, it does of course constitute a grave violation of Bolivian law, i.e. the **emission limit values of 0.2 [mg/l] CN^-** as of CN^-_{FREE} [48, MDSMA, 1995, p.200].

Equally significant are the gaps and inconsistencies of EMIRSA's monitoring reports, which make it difficult to assess the environmental performance of the Kori Kollo goldmine. This includes the omission of measured values, inconsistencies with externally commissioned measurements, and contradictions between EMIRSA's own measurements of elevated values (mentioned above) and the subsequent claim that nearly all investigated wells featured zero values of cyanide concentrations. Taken together, these points may indicate an attempt to obscure certain aspects of the environmental performance that could not be dismissed by interviewed EMIRSA staff [47, Columba, 2007].

On a more detailed level, EMIRSA's monitoring neglected certain aspects of a truly comprehensive approach to environmental monitoring. While the ambient air monitoring programme examined only two parameters – the total suspended particles value (TSP) and PM-10 – it failed to examine the parameters of shape of particles and the chemical composition of the dust. This does not violate any specific BAT norms or standards, but should not be discounted36).

Beyond these general points of doubt, the BAT established by the European Commission and non-European authorities provide a specific and elaborated framework for an assessment of EMIRSA's environmental performance. Both are based on the "International Cyanide Management Code for the Manufacture, Transport and Use of Cyanide in the Production of Gold" [8, ICMI, 2010], but foreground different aspects. Hence, they can be taken as complementary frameworks.

4.3.1 Comparison with Best available techniques (BAT)

One of the most severe claims made against EMIRSA concerns the alleged **overtopping of evaporation ponds**. Specifically, [14, Montaya & Mendieta, 2006, p.51] raises accusations regarding overtopping of evaporation ponds after heavy rainfalls in the years 1999-2003 which supposedly contaminated the surrounding area, causing salinization and contamination of soil by heavy metals. EMIRSA has denied any such contamination [47, Columba, 2007]. While Montaya & Mendieta's argument seems plausible, since it relies on meteorological data, no conclusive evidence of actual contamination was found.

In the first processing plant of the Kori Kollo gold mine, referred to as San Andrés, the **leaching pad was not prepared with a liner** as required by BAT. In fact, the above-mentioned elevated cyanide values may well have been the result of the failure to install a liner at this early stage. This conclusion is corroborated by the fact that the two monitoring wells in question were, indeed, located in close proximity of the processing plant San Andrés.

EMIRSA documentation of **the day-to-day operations** regarding measures **to reduce cyanide consumption** during the leaching process indicates a **likely violation of BAT standards**.

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36) The shape and size of a particle can influence significantly its hazard potential. For example, asbestos fibres are naturally occurring mineral silicates. A particle is classified as a fibre when it is longer than 5 μm and the ratio of length to thickness is greater than 3:1. For example, the chemical composition of asbestos fibres as such does not make them toxic. However, asbestos fibres pose health risks at respirable sizes, whereat long fibres are more carcinogenic than short ones. USEPA and the International Agency for Research on Cancer (IARC) have classified asbestos as a human carcinogen by inhalation. [49, ToxProbe , 2002]

According to [9, European Commission, 2009, p.434], BAT includes operational strategies to minimize cyanide addition, automatic cyanide control and, if applicable, peroxide pretreatment. None of these were found in the investigated documentation of the Kori Kollo gold mine.

With respect to the omission of values prior to January, 1994, it must also be noted that EMIRSA's Manifiesto Ambiental claimed that – despite the admission of measurable values and ensuing incidental infiltrations – neither superficial waters, areas of agriculture or pasture, nor subterranean waters currently in use were affected. This formulation does not include future land-use and thus violates BAT standards [9, European Commission, 2009, p.332].

Precipitation in the area of the gold mine's operation was collected and discharged into two natural ponds. According to documentation, however, no further measures for treatment and control, e.g. assaying for contamination, were taken as recommended by BAT.

Despite the numerous points of substantial criticism directed against EMIRSA's actual environmental performance, the overall **planning** procedure for the Kori Kollo gold mine **seems to have been conducted with a technological standard approximating that of BAT**. Several of the above criticisms are, indeed, related to a lack of documentation, rather than to a documented violation or neglect of BAT (a fact that becomes abundantly clear in the comparison to the Australian guidelines on "best practice cyanide management"). There are, however, multiple aspects of documented compliance with respective standards.

EMIRSA documentation of the day-to-day operations regarding the discharge of slurried tailings into the tailings pond indicates compliance with BAT standards. According to [9, European Commission, 2009, p.434], BAT specifies that the remaining CN^{-}_{FREE} has to be destroyed prior to discharge into the tailings pond. Documentation shows that **this was carried out using the H_2O_2-process** from 1993 until 1995 and subsequently the **INCO SO_2/air-process** [4, Miller et al., 1997, p.128], both of which correspond to BAT standards.

In the first phase, i.e. the mining of oxidized ores, operations at the Kori Kollo gold mine furthermore complied with BAT standards in the following areas:

- EMIRSA included a closure plan for the gold mine in the initial planning phase of the project.
- The surface run-off was controlled by a collection system and then used as process water.
- EMIRSA used a closed water-cycle in the heap leaching process.
- Process water was used as a measure to reduce the emission of dust.

In the second phase, i.e. the mining of sulphide ores, operations at the Kori Kollo gold mine complied with BAT standards in the following areas:

- Solid tailings were decommissioned according to the guidelines of USEPA.
- All freshwater used at the gold mine was directed into the tailings pond.
- Approximately 25% of the water pumped from the pit was used as process water.
- Tank leaching applied technology according to BAT.
- In the case of spills, the affected area was treated with H_2O_2 or NaOCl for decontamination.

In summary, the comparison of EMIRSA's environmental performance with the BAT established by the European Commission shows **implausible and inconsistent documentation**, which – in and of itself – presents an obstacle in assessing the gold mine's actual performance.

However, only a few points of criticism can be based on hard facts that prove a violation of BAT standards, most notably EMIRSA's failure to consider successive land-use as well as the potentially related points of elevated values of cyanide concentrations and the failure to use a liner in the start-up phase of the project. With the exception of these, EMIRSA's documentation suggests that the gold mine's environmental performance generally complied with BAT.

4.3.2 Comparison with Best Practice Cyanide Management

In 2003 the Australian Federal Department of the Environment and Heritage published guidelines about cyanide management, including information on the International Cyanide Management Code. The guidelines were established drawing on advisers from the mining industry (the Sustainable Minerals Steering Committee), Australian federal and state government agencies, research institutions and mining-associated non-government organisations. It introduces ten "**commandments**" for achieving "**best practice cyanide management**" which can be considered state-of-the-art in cyanide management. [10, Needham, 2003]

Unlike the BAT defined by the European Commission, it focuses in greater detail on planning, management procedures and a consistent safety protocol. A complete listing of the ten requirements and a rated comparison to EMIRSA's environmental performance can be obtained from Table 12. The assessment uses three levels of compliance, where 1 represents good compliance, 2 is medium compliance and 3 means bad or non-existing compliance [50, Reichard et al, 2008].

Table 12 (part 1): EMIRSA's compliance with "best practice cyanide management", adapted from [50, Reichard et al, 2008].

(1) Implement an overall planning procedure, from conception to closure and rehabilitation, for all mine operations that use cyanide, based on an assessment of risks that maximises the benefits and minimises liabilities and environmental impacts		
Actions	*compliance*	*rating*
Exploration phase before starting the plant	Conception	2
Closure plan implemented 1995	Closure	2
Closure plan includes rehabilitation	Rehabilitation	2
Risk assessment: carried out	Risk assessment	3
(2) Establish, implement and regularly review a cyanide management strategy as part of the mine's environmental management plan for implementing best practice		
Cyanide spills: containment by H_2O_2, NaOCl	Establish strategy	2
pH-control by adding lime	Implement strategy	2
Closed water circuit: phase of oxidized ores	Review strategy	3
Rinsing and encapsulating of leached heaps	Implement "best practice cyanide management"	3
(3) Implement initial and ongoing cyanide safety and management training for all personnel involved in cyanide including contractors, who have management, operational or maintenance responsibilities or who handle or are exposed to cyanide – this training should cover both the everyday roles of personnel and how they respond to cyanide-related emergencies		
External safety training hired from DuPont	Everyday roles	1
Emergency groups in every shift	Emergencies	1
(4) Establish well-defined responsibilities for individuals with clear chains of command and effective lines of communication within the workforce		
Environmental supervisors established	Specific	2
	Chains of command	3
	Lines of	3
(5) Institute safe procedures for cyanide handling governing transport, storage, containment, use and disposal		
Packing: wooden boxes, 2 layers of PP+PE	transport	2
Storage: restricted area, wire-netting fence	storage	1
Containment: H_2O_2, NaOCl	containment	1
Programme: prevention of occupational risks	use	1
cyanide destruction: INCO-Process	disposal	3
(6) Integrate the mine's cyanide and water management plans		
No systematic approach, see (2)	integrate CN^- and H_2O	3
(7) Identify and implement appropriate options for minimising demand for cyanide, and reusing, recycling and disposing of residual cyanide from plant operations		
Reusing cyanide solution: phase of oxidized ores	Minimise demand	3
	Reusing/recycling	3
	Disposal	3
(8) Conduct regular cyanide audits and revise cyanide management procedures where appropriate		
None	Audits	3

Table 13 (part 2): EMIRSA's compliance with "best practice cyanide management", adapted from [50, Reichard et al, 2008].

(9) Develop a cyanide occupational and natural environment monitoring programme, supported through a sampling, sample preservation, analysis and reporting protocol		
Monitoring programme established	Developed	2
Field sampling: daily calibration, fresh containers	Sampling	2
	Analysis	3
	Reporting	3
(10) Establish a carefully considered and regularly practiced emergency response procedure		
Emergency groups established, see (3)	Emergency response	1

EMIRSA's compliance with "best practice cyanide management" achieves an **average rating of 2.25** on a scale from 1 to 3. The assessment is commented on below.

(1) The mining activities included an exploration phase from 1982-1985 and a closure and rehabilitation plan, which has been carried out since 1995 [44, Arze; 2007], amounting to a level 2 compliance. As far as the assessment of risks is concerned an implausible claim of no significant risk is stated [4, Miller et al., 1997, p.216], consequently rated as level 3.

(2) No overall cyanide management strategy was found. In both phases cyanide spills were contained by H_2O_2 and NaOCl and pH control was carried out with the help of lime. During the phase of oxidized ores the process water was used in a closed circuit. Leached heaps were taken care of by rinsing with fresh water and encapsulation. When the first phase was closed, the process water was reused in the plant for sulphide ores. However, these first signs suffer from a lack of systematic approach. This certifies a level 2 compliance in establishing and implementing a cyanide strategy. No tool for reviewing procedures was established and no efforts were made for implementing "best practice cyanide management", resulting in level 3 rating for these areas.

(3) There are 2 systems meeting the need for cyanide safety and management training. The American enterprise E. I. du Pont de Nemours and Company (DuPont) was hired and held courses referred to as STOP (seguridad en el trabajo por la observación preventiva – occupational safety by preventive observation) for members of top and middle management. The second institution is made up of emergency teams recruited from workers in every shift, regularly trained in first aid, intoxication and fire fighting [4, Miller et al., 1997, pp.196-197]. As a consequence, satisfactory compliance (level 1) for the training in everyday roles and emergencies was attested.

(4) EMIRSA's management provides for environmental supervisors, which earns EMIRSA a rating of 2 in defining responsibilities but it fails to elaborate on clear chains of command and communication, resulting in level 3 rating, respectively.

(5) EMIRSA provided no information on the means of transportation for cyanide. Solid NaCN was delivered in wooden boxes lined with two layers of polypropylene (PP) and polyethylene (PE). Since safe packing is part of safe transportation, level 2 compliance can be attested. [4, Miller et al., 1997, p.151]

Safe storage of cyanide was guaranteed (level 1) by storing the chemical in a restricted area protected by a wire-netting fence. Also, containment of cyanide spills was met accordingly (level 1) - see (2). Safe procedures in cyanide use were introduced by a programme of prevention of occupational risks, adding a level 1 rating to the record. [4, Miller et al., 1997, p.191]

The subject of **disposal of cyanide** is **questionable**. On the one hand the INCO-Process (oxidation of cyanide to cyanate with SO_2 and air) for cyanide destruction was installed in 1996 and before that date cyanide was treated with H_2O_2 before deposition into the tailings pond. Both procedures are common practice in the mining industry and comply with BAT. On the other hand, high values of cyanide were measured in two monitoring wells (peaks of **0.88 [mg/l] CN^-** at the **well PFSA-4** in January 1994 and **18.58 [mg/l] CN^-** at the **well PFSA-5** in January 1995), exceeding both Bolivian [48, D.S. 24176, 1995, p. 200] and international [11, USEPA, 1994, p.29] permissible limits of **0.2 [mg/l] CN^-** as of CN^-_{FREE}. However, this incidence was neither dealt with accordingly by EMIRSA at the time of occurrence (1994/1995) nor when EMIRSA was confronted with the subject in 2007 [47, Columba, 2007]. As a consequence this disputable behaviour results in level 3 rating of the issue of cyanide disposal.

(6) No evidence for the integration of cyanide and water management plans was found. Therefore a level 3 rating is attested. See (2) for corresponding information.

(7) No evidence of attempted minimisation of primary cyanide demand was found. Reusing took place during the phase of oxidized ores, as indicated in (2), but was not continued in the sulphide phase. The aspect of disposing of residual cyanide has already been discussed in (5). Consequently an overall rating of level 3 applies for (7).

(8) No documents were found on cyanide audits. This results in a level 3 rating.

(9) A monitoring programme observing air and water was installed at EMIRSA. Field sampling is described, including daily calibration of instruments and use of fresh sampling containers [5, Miller et al.; 1999; p.238A]. The results of analysis as well as reporting are not considered trustworthy as certain irregularities in measured high cyanide levels - see (5) - and contradictory reporting within the same document issued by EMIRSA have occurred [50, Reichard et al, 2008]. As a consequence a level 3 rating is given for analysis and reporting, also dragging the previous steps of development and sampling down to level 2.

(10) The tenth commandment is met satisfactorily, see (3), acknowledged by a level 1 rating.

The **average rating of 2.25** given to EMIRSA's compliance with "best practice cyanide management" indicates a severe non-compliance with the respective standards. In particular the following areas were found lacking: risk assessment, implementation of best practice standards, clear chains of command and lines of communication, minimising demand for cyanide (including reuse and recycling), disposal of residual cyanide from plant operations, and review of the cyanide management strategy.

5 Conclusions

The Kori Kollo gold mine, situated in Oruro, Bolivia, has been in operation since 1982 [1, Peró et al., 1992, pp. 1-2]. In the course of the ongoing mine life, the gold mine's owner, **Empresa Inti Raymi S.A. (EMIRSA)**, has been confronted by severe accusations and over 800 complaints concerning contamination and other environmental problems in the surrounding area. However, the majority of accusations lacked objectivity, giving room for populist argumentation and further emotionalizing the already sensitive situation.

This Thesis represents a scientifically grounded evaluation of the environmental performance of the Kori Kollo gold mine, based on its overview of the state-of-the-art in cyanide leaching in gold mining37). In order to achieve this aim, the following objectives were defined for this Thesis:

(1) Providing an overview of the state-of-the-art of the extraction of gold, focusing on managing the crucial aspects of acid rock drainage, tailings and waste-rock as well as cyanide as basis for the following investigation of the environmental performance of the Kori Kollo gold mine.

(2) Investigating and documenting the environmental performance of the Kori Kollo gold mine (Oruro, Bolivia) from 1982 until 2003.

(3) Comparing the environmental performance at the investigated Kori Kollo goldmine from 1982 until 2003 to the state-of-the-art as specified for the purposes of this Thesis.

The defined objectives were achieved in the following manner:

As introduction to the subject; the background of gold extraction was described from two points of view in chapter 2. In chapter 2.1 an overview of the properties of gold, which entail its appreciation, was provided.

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37) Scientific works on this subject have been presented by the author of this Thesis on three international conferences:

- International Conference on Clean Technologies for the Mining and Metallurgical Industry (ICCTMMI), Arequipa, Peru, September 24-26, 2007.
- International Conference on Clean Technologies for the World Mining Industry (CTWMI), Santiago de Chile, April 13-16, 2008.
- DepoTech 2008, Leoben, Austria, November 12-14, 2008.

The panel discussions at these conferences and the suggestions from the respective approval committees have helped to refine the presented results.

This chapter also contains an overview on global supply and demand, pointing out global geological reserves of gold as well as analysing the trends in gold production of the top six gold producing nations of the years 2004-2009.

It was found that China has pushed its gold production to first position since 2007, despite only ranking on eighth position in geological reserves of gold. The greatest geological reserves of gold are found in South Africa.

In Chapter 2.2 the process of gold extraction was described, featuring the basic unit operations of a gold extraction flow-sheet and focussing especially on the use of cyanide in gold extraction. Cyanide is a very effective chemical allowing the mining of ores down to (or even below) a **cut-off gold of 0.3 [g/t]** in **surface mining** and **3.0 [g/t]** in **underground mining** [31, AngloGold Ashanti, 2008, pp.1, 8]. Out of this reason, cyanide leaching of gold ores has become the most commonly used technology for the extraction of gold. However, the same chemical properties (its tendency to form stable metal-cyanide complexes) which make cyanide so effective from the gold mining point of view, is causing the high toxicity of cyanide for most living organisms.

Apart from the toxicity of cyanide, gold mining entails further environmental impacts by producing large amounts of waste-rock, tailings and a phenomenon associated with the mining of sulphide ores referred to as acid rock drainage (ARD).

In view of the rising demand for gold38) laid out in chapter 2.1 on the one hand and severe environmental impacts of gold mining on the other hand the only way of making ends meet lies in responsible management with a holistic approach of the mentioned paramount waste issues waste-rock, tailings and acid rock drainage and cyanide management, as expressed in the cradle-to-grave concept, which was provided in chapter 3. In accordance with the aim of considering as many relevant aspects as possible, the origin, the characteristics and the prevention/mitigation methods were described. In doing so, the first objective was met.

The ensuing chapter was dedicated to introducing the investigated Kori Kollo gold mine (chapter 4.1) and the investigation of the environmental performance (chapter 4.2) which achieved accomplishment of the second objective. Finally, the environmental performance of the gold mine was compared to the European standards of "best available techniques", i.e. BAT, established by the European Commission and, for additional evaluation, to the Australian standards of "best practice cyanide management".

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38) This reminds of Johann Wolfgang von Goethe who expressed the rush for gold in his play Faust, part one, where Margaret says [51, Goethe, 1808]:

"To gold still tends, on gold depends, all, all!"

These frameworks have been created in response to several catastrophic accidents – most prominently the dam failures at Aznalcóllar (Spain) in 1998 and Baia Mare (Romania) in 2000 – and with the aim of serving as reference guidelines to optimise the environmental performance of mining operations [9, European Commission, 2009, pp.xli, 427].

The evaluation of the environmental performance provided accomplishment of the third objective of this Thesis and may be summarized as follows:

The comparison with the European BAT, which focuses on technological specifications and operations, led to an assessment that showed only a handful of clear violations. It was, however, severely limited by the fact that EMIRSA's documentation lacked considerable details and consistency.

Since aspects of monitoring, documentation and management processes are emphasized and fore-grounded by the Australian guidelines for "best practice cyanide management", the resulting assessment is considerably more damning than the one following BAT. Critical shortcomings and lacks could be identified relating to risk assessment, clear chains of command, minimising the demand for cyanide, the disposal of residual cyanide, and the clear definition of a cyanide management strategy.

6 Indices

6.1 References

[1] Peró, M., Meneses, C., Zelaya, O. (1992): El medio ambiente dentro de la actividad minera en la Empresa Minera Inti Raymi S.A. In: Empresa Minera Inti Raymi S.A. (Editor): *Proceedings of El Ambiente En La Minería 1992*. International seminar on The Environment in Mining. 18-19 May 1992, Santiago de Chile, Chile

[2] Storm, P. (2010): Personal Communication with the Managing Director of Raw Materials Group, Sweden, Email from per.storm@rmg.se on September 13, 2010.

[3] U.S. Geological Surveys (USGS 2010a) (2010): 2008 Minerals Yearbook – Gold. Online information downloaded from http://minerals.usgs.gov/minerals/pubs/commodity/gold/index.html#myb on August 7, 2010.

[4] Miller, S., Rejas A., Zambrana J. (1997): Manifiesto Ambiental Mina Kori Kollo. Vol 1-3., La Paz, Bolivia: Empresa Minera Inti Raymi S.A. (Editor), 1997.

[5] Miller, S., Rejas A., Zambrana J. (1999): Manifiesto Ambiental Mina Kori Kollo. Vol 1-3., amendment January, 1999, La Paz, Bolivia: Empresa Minera Inti Raymi S.A. (Editor), 1999.

[6] BMFLUW (2000): Federal Act on Environmental Impact Assessment of August 10, 2000. In: Federal Law Gazette (FLG) No. 697/1993 as last amended by FLG No. I 89/2000. English translation by: Austrian Federal Minister of Agriculture and Forestry, Environment and Water Management, 2005. Downloaded from http://www.ris.bka.gv.at/Dokument.wxe?Abfrage=Erv&Dokumentnummer=ERV_1993_697 on September 26, 2010.

[7] European Union (EU) (2003): Directive 85/337/EEC of the Council of the European Union of 27 June 1985 on the assessment of the effects of certain public and private projects on the environment, as last amended by Council Directive 2003/35/EC of 26 May 2003. In: Official Journal of the European Union L 156, 25/06/2003 pp. 17-25

[8] International Cyanide Management Institute (ICMI) (2010): Online information from http://www.cyanidecode.org viewed on August 6, 2010.

[9] European Commission (EC) (2009): Reference Document on Best Available Techniques (BAT) for Management of Tailings and Waste-Rock in Mining Activities, 2009. Downloaded from http://eippcb.jrc.ec.europa.eu/reference/brefdownload/download_MTWR.cfm on December 21, 2009.

[10] Needham, S. (2003): Best Practice Environmental Management in Mining – Cyanide Management: Federal Department of the Environment and Heritage, Australia, Commonwealth of Australia (Editor), 2003.

[11] U.S. Environmental Protection Agency (USEPA) (1994): Technical report – Treatment of cyanide heap leaches and tailings, Washington, DC: Office of Solid Waste, Special Waste Branch (Editor), 1994. Online information downloaded from www.epa.gov/osw/nonhaz/industrial/special/mining/techdocs/cyanide.pdf on October 25, 2010.

[12] Lorax Environmental Services (2000): Lixiviación de óxidos en pilas: Fase V., La Paz, Bolivia: Empresa Minera Inti Raymi S.A. (Editor), 2000.

[13] Batuani, P., Cardenas, V (2003).: Un ejemplo de minería, desarollo sostenible y responsibilidad social, CD-ROM. La Paz, Bolivia: Empresa Minera Inti Raymi S.A. (Editor), 2003

[14] Montoya, J.C., Mendieta, R.S., (2006): Salinización y Metales Pesados – Evaluación ambiental de la mina Kori Kollo (EMIRSA) en el área de influencia, con aplicación de la Teledetección SIG, Oruro: Centro de Ecología y Pueblos Andinos (CEPA) (Editor), 2006. – ISBN 99954-30-18-5.

[15] Newmont Waihi Gold Limited (2010): Online Information from http://www.marthamine.co.nz viewed on September 26, 2010.

[16] Hoyt, C. (1985): Precious Metals – Gold. In: Weiss, N. (Editor): SME (Society of Mining Engineers) Mineral Processing Handbook, New York, 1985. – ISBN 0-89520-433-6

[17] Marsden, J., House, C. (2006): The chemistry of gold extraction, second edition, Littleton: Society for Mining, Metallurgy and Exploration, Inc. (Editor), 2006.

[18] McQuiston jr, C. (1985): Precious Metals – Introduction. In: Weiss, N. (Editor): SME (Society of Mining Engineers) Mineral Processing Handbook, New York, 1985. – ISBN 0-89520-433-6

[19] Merriam-Webster, Incorporated (2010): Online Information from http://www.merriam-webster.com/dictionary/malleability viewed on September 26, 2010.

[20] U.S. Geological Surveys (USGS b) (2010): Mineral Commodity Summaries 2010. Online information downloaded from http://minerals.usgs.gov/minerals/pubs/mcs/ on July 8 2010.

[21] Klapwijk, P. (2010): Gold Survey 2010. Gold Fields Mineral Services Ltd (Editor). Online information downloaded from http://fliiby.com/get/834147/Gold-Survey-2010-Presentation_London_public-6pgt5lfuli.html
on July 8, 2010.

[22] Herz, N. (1985): Historical Developments in Milling of Gold Ores. In: Weiss, N. (Editor): SME (Society of Mining Engineers) Mineral Processing Handbook, New York, 1985. – ISBN 0-89520-433-6

[23] Tiess, G. (2010): Personal communication with scientific staff at the Chair of Mining Engineering and Mineral Economics, Department of Mineral Resources and Petroleum Engineering, University of Leoben, Austria on July 13, 2010.

[24] European Commission (EC) (2010): Europe in figures – Eurostat yearbook 2009. Online information downloaded from http://epp.eurostat.ec.europa.eu on July 7, 2010.

[25] Young, C. (2005): Cyanide Remediation: Current and past Technologies. Online information downloaded from www.dtsc.ca.gov/HazardousWaste/Cyanide/upload/CN_remediation_young.pdf
on August 7, 2010.

[26] Noller, B. (2008): Cyanide Management – Leading Practice Sustainable Development Program for the Mining Industry, 2008. – ISBN 0 642 72593 4. Online information downloaded from http://www.ret.gov.au/resources/Pages/Publications.aspx on July 17, 2009

[27] Klenk, H. et al. (1987): Cyano Compounds, Inorganic. In: Gerhatz, W. (Editor): Ullmann's Encyclopedia of Industrial Chemistry, fifth completely revised edition, Weinheim: VCH Verlagsgesellschaft mbH, 1987. – ISBN 3-527-20108-4, pp. 159-190

[28] Menapace, H. (2007): Behandlung von gefährlichen Abfällen – Vorlesungsunterlagen zur Vorlesung LV.Nr. 510.070. Leoben: Montanuniversität Leoben, Institut für nachhaltige Abfallwirtschaft und Entsorgungstechnik (Editor), 2007.

[29] Tiess, G. (2009): Rohstoffpolitik in Europa – Bedarf, Ziele, Ansätze, Wien: Springer-Verlag, 2009. – ISBN 978-3-211-09451-5

[30] Flachberger, H. (2010): Personal communication with the Head of the Chair of Mineral Processing, Department of Mineral Resources and Petroleum Engineering, University of Leoben, Austria on July 19, 2010

[31] AngloGold Ashanti Limited: AngloGold Ashanti Announces Significant Exploration Results at 100% Owned La Colosa Project in Colombia – Online information viewed on http://www.anglogoldashanti.com on July 3, 2010

[32] World Gold Council (2010): Online information from http://www.marketknowledge.gold.org/ viewed on November 14, 2010

[33] Alkane Resources LTD (2010): Annual Report 2009. Online information downloaded from http://www.alkane.com.au/reports/annual/default.shtml on July 3, 2010

[34] Antrekowitsch, H. (2010): Vorlesungsunterlagen zu Metallhüttenkunde II. Leoben: University of Leoben, Department of Metallurgy - Chair of Nonferrous Metallurgy (Editor), 2010

[35] Austrian Government (2010): Bundesgesetz vom 16. Juli 2002 über eine nachhaltige Abfallwirtschaft (Abfallwirtschaftsgesetz 2002 – AWG 2002) in der Fassung vom 19. Oktober 2010. In: BGBl. I Nr. 102/2002

[36] Lebensministerium (BMLFUW) (2006): Key features of Austrian Waste Management Strategy, 2006. Homepage of the Austrian Federal Waste Management Plan. Online Information from http://www.bundesabfallwirtschaftsplan.at/article/archive/16470 viewed on September 28, 2010

[37] European Union (EU) (1996): Directive 96/61/EC of the Council of the European Union of 24 September 1996 concerning integrated pollution prevention and control (IPPC Directive). In: Official Journal of the European Union L 257, 10/10/1996 pp. 26-40

[38] Kaiser, E. (2007): Umweltaspekte der Nichteisenmetall- sowie Golderzindustrie. Bachelor thesis, Chair of Mining Engineering and Mineral Economics, Department of Mineral Resources and Petroleum Engineering, University of Leoben, Austria (Editor), 2007.

[39] European Union (EU) (2006): Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the management of waste from extractive industries. In: Official Journal of the European Union L 102, 11/04/2006 pp. 15-34

[40] Thomé-Kozmiensky, K., Lorber, K,. (2010): Review of the project involving a technology for reclamation on the southern heaps of the former open-pit copper mine "Vlaikov Vrach", Bulgaria – Expertise submitted to EKO MEDET Ltd. Panagjurski Kolonii, Bulgaria, 2010

[41] Sarna, P. (2002): An Investigation of the use of limestone and lignite for the treatment of acid mine drainage. Master Thesis, Department of civil engineering, Indian Institute of Technology, Kanpur (Editor), 2002

[42] World Information Service on Energy (WISE) Uranium Project. (2010) Online information viewed on http://wise-uranium.org/mdaf.html on October 26, 2010

[43] Columba, M. (2010): Personal communication with the supervisor of Environmental Control of Empresa Minera Inti Raymi S.A., Bolivia, Email from mcolumba@emirsa.com on October 7, 2010

[44] Arze, J. (2007): Personal communication with the Head of the Department of Environmental Control of the Kori Kollo mine, Bolivia, on July 7, 2007

[45] P.C.A. Ingenieros Consultores S.A. (2010): Auditoria Ambiental a las Operaciones Mineras Kori Kollo Empresa Minera Inti Raymi – Informe fase I., La Paz, Bolivia: Ministerio de Medio Ambiente y Agua (Editor). Online Information downloaded from the homepage of the Bolivian Ministry of the Environment and Water (MMAyA): http://www.mmaya.gob.bo/web_anexo/medioambiente/auditoria_ambiental/auditoria_amb.php on November 6, 2010

[46] Minería de Bolivia – Noticias de mineria en Bolivia, empresas, minas y cotización de minerales (2010): Online information from http://boliviaminera.blogspot.com/2010/08/auditoria-ambiental-de-kori-kollo.html, viewed on August 25, 2010

[47] Columba, M. (2007).: Personal communication with the supervisor of Environmental Control of Empresa Minera Inti Raymi S.A., Bolivia, on September 4, 2007

[48] Ministerio de Desarollo Sostenible y Medio Ambiente (MDSMA) (1995): Reglamento en Materia de Contaminación Hídrica (RMCH) del 8 de Diciembre de 1995. Decreto Supremo (D.S.) N^{o} 24176. Downloaded from http://www.siabolivia.com/legambbol.html on September 9, 2010

[49] ToxProbe Inc. (2002): Ten Carcinogens in Toronto, 2002. Downloaded from www.toronto.ca/health/pdf/cr_appendix_b_asbestos.pdf on August 29, 2010

[50] Reichard, T., Rocha, J., Lorber, K. (2008): Environmental impacts of gold recovery at a leading gold mining enterprise in Bolivia, South America. In: Sánchez, M., Valenzuela, A., Chaparro, E., Reghezza, A., Álvarez, J. (Editors): Advances in Cleaner Technologies for the Mining and Metallurgical Industry, proceedings of the international conference, Santiago de Chile, Chile, 2008, pp. 213-225

[51] Goethe, J. (1808): Faust part 1, Scene VIII: Evening – A neat little room; Stuttgart: Cotta, 1808. English translation by: Taylor, B., 1871. Downloaded from http://www.gutenberg.org/etext/14591 on August 16, 2010

6.2 Abbreviations and Acronyms

Abbreviation	Explanation
$\overset{\oplus}{V}$	Throughput, defined for the purposes of this Thesis as litre per squaremeter per minute [l/m^2/min]
[ ]	Indication of a unit as in [g/l] or indication of reference as of [numer of reference, year of publication, page] or concentration of substance as in $[CN^{-}]$
$[CN^{-}]$	Concentration of cyanide ions
[g/l]	Gram per litre
[g/t]	Gram per ton
$[H_3O^+]$	Concentration of hydrogen-ions
[mg/l]	Milligram per litre
[tpd]	Tons per day
µ	Micro, as of the millionth (10^{-6}) part
µm	Micrometer, also referred to as micron, as of the one millionth (10^{-6}) part of one meter
Ag	Silver
ALFA/Teclimin	América Latina Formación Académica/Tecnologías Limpias en la Indstria
AMD	Acid mine drainage
AP	Acid Potential
aq	Aqueous
ARD	Acid rock drainage
Au	Gold
AVR	Acidification-Volatilization-Recovery
BAT	Best available techniques
BGBl	Bundesgesetzblatt

$C\equiv N$	The cyano group
$C\equiv N^-$	Cyanide ion with one carbon atom triply bonded to one nitrogen atom
$Ca(OH)_2$	Calcium hydroxide
CaO	Calcium oxide
CAP	Capacity
CIL	Carbon-in-leach
CIP	Carbon-in-pulp
cm	Centimeter, as of the one hundredth (10^{-2}) part of one meter
CN^-	Cyanide ion
CN^-_{FREE}	Free cyanide
CN^--solution	Cyanide solution
CN^-_{TOT}	Total cyanide
CN^-_{WAD}	Weak acid dissociable cyanide
CO_2	Carbon dioxide
Cu	Copper
d	Day (English) or dies (Latin)
D.S.	Decreto Supremo
e.g.	Example given (English) or exempli gratia (Latin)
EC	European Commission
EEC	European Economic Community
EIPPCB	European Integrated Pollution Prevention and Control Bureau
EMIRSA	Empresa Inti Raymi S.A.
et al.	And other (English) or et alii (male), et alliae (female), et alia (neutrum) (Latin)

etc.	And the rest or and other things or and so forth (English) or Et cetera (Latin)
EU	European Union
Fe^{2+}	Ferrous iron
Fe^{3+}	Ferric iron
FeAsS	Arsenopyrite
FeS	Pyrrotite
FeS_2	Pyrite
FLG	Federal Law Gazette
g	Gram
GFMS	Gold Fields Mineral Services Ltd.
H_2O_2	Hydrogen Peroxide
HCl	Hydrogen chloride
HCN	Hydrocyanic acid
HDPE	High Density Polyethylene
i.e.	That is (English) or id est (Latin)
IARC	International Agency for Research on Cancer
INCO	International Nickel Company of Canada
INSO	Instituto Nacional de Salud Ocupacional
IPPC	Integral Pollution Prevention and Control
IPTS	Institute for Prospective Technological Studies, Sevilla, Spain
KCN	Potassium cyanide
Kgpd	Kilogram per day
$l/m^2/min$	Litre per squaremeter per minute
log	Decadal logarithm

m	Meter or milli, as of the thousandth (10^{-3}) part
m^3/d	Cubic meters per day
mg	Milligram, as of the one thousandth (10^{-3}) part of one gram
n.a.	Not applicable
n.d.a.	No data available
NaCN	Sodium cyanide
NaOCl	Sodium hypochlorite
NaOH	Sodium hydroxide
NH_3	Ammonia
NH_4^+	Ammonium
NP	Neutralisation Potential
NPR	Neutralisation Potential Ratio
Pb	Lead
PE	Polyethylene
PFSA	Name of monitoring well
pH	Potentia hydrogenii (Latin) as of the negative decadal logarithm of the concentration of hydrogen-ions, - log [H_3O^+]
PM-10	Particulate matter of ten micrometer in diameter or smaller
PP	Polypropylene
ppm	Part-per-million
RMCH	Reglamento en Materia de Contaminación Hídrica
ROM	Run-of-mine
S.A.	Sociedad Anónima

SO_2	Sulphur dioxide
TDS	Total dissolved solids
TMF	Tailings management facility
TSP	Total suspended particles
TSP	Total suspended particles
TWG	Technical Working Group
U.S.	United States
USD/oz	United States Dollar per ounce troy
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
Zn	Zinc

6.3 Tables

6.4 Figures