

CHALMERS



Environmental Impacts and Health Aspects in the Mining Industry

A Comparative Study of the Mining and Extraction of Uranium, Copper and Gold

Master of Science Thesis in the Master Degree Programme Industrial Ecology

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Göteborg, Sweden, 2008
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Loading of a Caterpillar 793 haul truck with a Bucyrus electric cable shovel at Aitik copper mine, Sweden 2008-09-08. Private photo.

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Abstract

This thesis work has analysed environmental impacts and health aspects in the mining industry of copper, uranium and gold with the aim of determining the relative performance, in a given set of parameters, of the uranium mining industry. A selection of fifteen active mining operations in Australia, Canada, Namibia, South Africa, and the United States of America constitute the subject of this study. The project includes detailed background information about mineral extraction methods, the investigated minerals and the mining operations together with descriptions of the general main health hazards and environmental impacts connected to mining. The mineral operations are investigated in a cradle to gate analysis for the year of activity of 2007 using the economic value of the product at the gate as functional unit. Primary data has been collected from environmental reports, company web pages, national databases and through personal contact with company representatives. The subsequent analysis examines the collected data from a resource consumption, human health and ecological consequences point of view. Using the Life Cycle Impact Assessment methodology of characterisation, primary data of environmental loads have been converted to a synoptic set of environmental impacts. For radiation and tailings issues, a more general approach is used to address the problem. Based on the collected data and the investigated parameters, the results indicate a presumptive relative disadvantageous result for the uranium mining industry in terms of health aspects but an apparent favourable relative result in terms of environmental impacts. Given the prerequisites of this study, it is not feasible to draw any unambiguous conclusions. Inabilities to do this are mainly related to inadequate data availability from mine sites (especially in areas concerning tailings management), and difficulties concerned with the relative valuation of specific performance parameters, in particular radiation issues. Further studies are recommended within tailings management issues, preferably performed at site, and for studies with a broader sustainability approach.

Disclaimer

The findings of this report are based on primary data from various sources. However the data has been interpreted and treated by the authors in order to obtain comparable parameters. Furthermore, the authors have tried to critically review all data used but cannot guarantee its validity. Although great care has been taken to maintain the accuracy of the information provided in this report, the authors do not assume any responsibility for consequences that may arise from its use and the report cannot guarantee that general information or original data from mining companies have been interpreted correctly. Finally, the report does not reflect the views of Vattenfall AB.

Sammanfattning på svenska

Under de senaste åren har växthuseffekten och den globala uppvärmningen diskuterats flitigt i flera medier. Detta har lett till ökad efterfrågan på mindre koldioxidintensiva energikällor. I denna debatt har kärnkraften framförts som ett klimatvänligt alternativ. Frågetecken har dock uppkommit angående brytningen av den råvara som används som bränsle i kärnreaktorer, uran, och hur stor miljöpåverkan denna verksamhet egentligen har. Målet med detta examensarbete har varit att utröna huruvida uranbrytning ur ett miljö- och hälsoperspektiv generellt sett är mer eller mindre allvarlig än annan mineralbrytning.

Gruvbrytning i allmänhet är förknippat med stora konsekvenser för miljö och natur. Förutom tydliga sår i jordskorpan märks också utsläpp av många miljö- och hälsofarliga ämnen. Stora problem är framförallt förknippade med gruvavfallet som för lång framtid kan orsaka försurning och utsläpp av tungmetaller som finns bundna i malmrester. Olika mineral förekommer i olika former av malmer vilka i sin tur är förknippade med miljökonsekvenser av varierande allvarlighetsgrad.

För att genomföra studien har femton gruvor valts ut i olika delar av världen vilka har studerats i detalj för att med hjälp av denna information försöka dra generella slutsatser. Studien har begränsats genom att enbart undersöka gruvor som bryter någon utav mineralen koppar, guld eller uran.

Resultaten tyder på att urangruvor kan medföra allvarligare konsekvenser ur ett hälsoperspektiv men att övriga gruvor påvisar skadligare konsekvenser ur ett miljöperspektiv. Studien har dock inte haft möjligheten att täcka in samtliga områden som kan vara av intresse för att med säkerhet kunna ställa ett entydigt svar på frågan om uranbrytning generellt är mer eller mindre allvarlig än annan mineralbrytning ur ett miljö- och hälsoperspektiv. Vidare studier anses nödvändiga för att studera viss problematik mer djupgående för att på så vis kunna dra mer definitiva slutsatser.

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1 Introduction

In an era of increased attention to global warming, less carbon intensive energy sources are requested to a large extent. In the light of this, the nuclear industry has witnessed a minor renaissance. Consequently, increased demand of uranium has led to increased prices of this commodity and resources that were previously not profitable to mine have attracted new interest (WNA: The Nuclear Renaissance 2007).

However, the extraction of uranium constitutes the part of the nuclear fuel cycle with the largest environmental impact (Vattenfall AB Generation Nordic 2007). For obvious reasons, the mining of uranium has therefore attracted considerable advertency in terms of environmental concerns. The use of mineral resources, and thus also mining, is per definition unsustainable since it is based on the production of non-renewable resources from finite deposits. Furthermore, mining potentially causes severe environmental consequences and some of the worst industrial disasters are mining related (Aswathanarayana 2003).

Having said this, without challenging the environmental inconveniences connected to mining, and assuming that there is a presumptive future demand of uranium that has to be replenished by the extraction from geological resources; does uranium mining differ in terms of environmental impacts compared to the mining of other mineral commodities?

This is a question of particular interest in regions with rich holdings of mineral resources in general and of uranium resources in particular. General opinions about uranium mining are commonly strongly negative (e.g. Larsson 2008) while mining of other commodities often is met with great enthusiasm (e.g. Lövgren 2008). Is this a rational behaviour, when considering only the extraction of the different minerals respectively?

This project will try to shed some light to this issue by investigating environmental impacts and health aspects in the mining industry in a comparative study of the mining and extraction of uranium, copper and gold.

2 Project Outline

The structure of this report pursues the following outline. Initially, the problem and how it is addressed is defined in general, and in time and space in particular in order to present the prerequisites and limitations of the study. This is accounted for in the *“Goal and Scope”*.

Thereafter the reader is introduced to some background information about the mining industry and the different processes it comprises. Furthermore, the general problems of the industry in terms of the environment and human health are described. Special attention is given to the areas of radiation and tailings. This is described in the parts: *“Mineral Extraction”* and *“Health and Environment in the Mining Industry”*.

The subsequent parts of the report, *“Investigated Minerals”*, *“Investigated Mines”* and *“Companies Operating the Mines”*, describe the investigated minerals: uranium, copper and gold, the specific mines that are included in the study and the companies responsible for their operations.

After that, the methodology is explained and the results from the data inventory are presented and analysed in terms of environmental impacts and health aspects. This is performed in *“Methodology”* and *“Results and Analysis”*.

Finally, conclusions from the study are presented and explained together with discussions dealing with the validity of the findings and suggestions to further research.

The end of the report contains a complete list of referred literature and data sources, and detailed raw data from the data collection, available in appendix.

3 Goal and Scope

The following part will describe the background of the project and define the problem and its system boundaries, limitations and how it will be addressed.

3.1 Background

The authors' interest in this particular issue originated from a broadcast in November 2007 called "Uppdrag granskning" ("*Mission to Investigate*" freely translated) by the public Swedish television dealing with environmental issues of the Australian uranium mining industry. In accordance with the supervisor at Vattenfall AB, Lasse Kyläkorpi, and the examiner at Chalmers University of Technology, Karin Andersson, the current problem definition was developed.

3.2 Problem Definition

The general question that is to be addressed in this study is whether or not uranium mining in average has a better or worse environmental performance or health impact than the mining of other commodities based on a given set of parameters.

3.3 Aim and Goal

The aim of the study is to compare health and environmental impacts from uranium mining with mining of other minerals. The goal is to determine the relative environmental performance of the mining and processing of the different minerals.

3.4 Method

The study has been performed in the form of an empirical study, which is both descriptive and inductive, based on primary data from specific mining operations in order to come up with a general conclusion.

In order to limit the investigation to a synoptic set of data, the mining of uranium will be compared with the mining of two other mineral commodities.

The minerals chosen for comparison are gold and copper, due to their similarities as well as differences, in order to obtain a wider picture. The market price for both uranium and gold is relatively high and hence the minerals can be recovered at low mineral grades. Copper, on the other hand, is priced significantly lower and is generally broken at ore grades higher than uranium and gold. In addition to this, copper is a well-known metal of high utility in the society.

The investigated mining sites were chosen based on their geographical location. Initially three different regions with active uranium mines were chosen. Based on this, copper and gold mines were selected in the same geographical region in order to exclude contingent regional variations in both geological prerequisites, and political and legal circumstances. Furthermore, the aim, which however proved to be difficult to fulfil to a large extent, was to find mines operated by the same companies in order to exclude variations based on company management and culture.

This study is mainly based on primary data provided by the corporations responsible for the operation of the mines or data available in public databases managed by national environmental authorities. Background information is compiled based on information provided in general literature in the area of mining and environment and also on information from interest groups and associations

within the mining industry. Information is completed and compared with findings made in peer reviewed scientific articles and publications from scientific associations.

The data collected has been compiled and classified into specific impact categories to allow for comparison.

3.5 Impact Categories

Collected data has been classified into the following impact categories; resource consumption, human health and ecological consequences and analysed based on the following parameters; resource consumption, global warming, human toxicity, ecotoxicity, photochemical ozone creation potential, acidification and eutrophication as suggested by Baumann and Tillman (2004). To allow for comparison, when applicable, data will be analysed with the aid of characterisation indicators to reduce the number of parameters.

3.6 System Boundaries

The nature of this study is a cradle to gate analysis investigating the impacts arising in all process steps from the extraction until the final product that leaves the site. The geographical boundaries are limited to what occurs at the sites of the mineral leases, which are performed by the companies conducting the extraction. However, in terms of environmental impacts and health aspects, a global perspective is used.

Electricity generated off site is included without accounting for the amount of primary energy used for the electricity production and related conversion losses.

The temporal system boundaries are set to include activities of active mines occurring within the year of 2007.

However, in terms of wastes generated at site and traces of the product contained in these wastes, such as waste rock and tailings, these are followed to the grave and analysed over a longer period of time.

Environmental impacts arising from the production of capital goods such as machinery and buildings are excluded from this study.

3.7 Functional Unit

The collected data has been expressed and analysed based on three parameters: namely the amount of ore mined, the amount of product produced, both expressed in tonnes, and the value of the product produced expressed in million US dollars. Due to the inability to compare the utility of the different commodities, and also because of differences in the nature of the final product at the different sites, the most appropriate functional unit was determined to be the value of the product at the gate.

In most cases, the final product at the gate is calcinated uranium octaoxide (U_3O_8), also known as yellow cake, in the case of uranium mining, and gold bullion and copper cathode in the case of gold and copper mining respectively.

3.8 Data Quality

Since the data used in this study mostly is provided by the companies operating the mines, there is little possibility to determine the validity of the data. However most of the information is found in environmental reports and sustainability reports, which often follow the guidelines set up by the Global Reporting Initiative (GRI).

The main problem with the data used is assumed to be differences in the way certain values are calculated and presented and what is included in the data. This uncertainty is further increased by the large variation of the sites in terms of age, mining methods, geology, climate and other local prerequisites.

3.9 Limitations

Although this report deals with uranium and parts of the nuclear fuel cycle, it has nothing to do with nuclear power generation and environmental consequences from that and it should not be used for such purposes.

The aim is merely to compare the activities conducted at the mining sites and it is important to emphasize the completely different utility of the different commodities. Impacts from the entire life cycle of the products may generate a completely different result.

Furthermore, activities of exploration apart from the continuous exploration conducted in active mines are not included. The majority of the data is based on one defined time period of the life of a well developed and active mine. Similarly, although the study briefly investigates the environmental prerequisites of the mine after closure by looking at waste and tailings generated during one year, it is important to stress the fact that unless the mine is rehabilitated in an appropriate way, it can continue to be an environmental issue for centuries.

4 Mineral Extraction

The U.S. Bureau of Mines defined in 1989 a mineral resource as “a concentration of naturally occurring solid, liquid or gaseous material in or on the earth’s crust in such a form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible”. The term “economic extraction” in the definition emphasizes the dynamics of what is a mineral resource. Ore is defined as “mineral or rock that can be recovered at profit” (Aswathanaryana 2003).

Mining can generally be divided into four phases: exploration, development, extraction and processing, and decommissioning (Ripley, Redman & Crowder 1996). Exploration is the defining of the extent and value of the ore (Hartman & Mutmansky 2002). During the development stage, the deposit is opened for production (exploitation or extraction), i.e. access is gained to the deposit. This is done by either stripping the overburden to expose the ore near the surface or by excavating openings as preparation for underground mining for deeper deposits (Hartman & Mutmansky 2002). This study will look further into the consecutive phase, the extraction and processing of the ore.

The following text will provide an overview of different mining methods and processes involved in the extraction of the mineral.

4.1 Mining

The choice of extraction method is based on the characteristics of the mineral, safety and environmental concerns, and technology and economics (Hartman & Mutmansky 2002). The most traditional methods are surface mining and underground mining. Surface mining can be further divided into mechanical excavation methods such as open-pit and open-cast mining and aqueous methods, of which leaching is the most common. Underground mining methods are usually divided into three classes: unsupported, supported and caving (Hartman & Mutmansky 2002).

4.1.1 Surface Mining

Surface mining is, as the name implies, mining methods of ore, coal, or stone that are carried out at the surface with basically no underground exposure of miners (Hartman & Mutmansky 2002). This group of mining methods is the dominating category worldwide (Hartman & Mutmansky 2002). Of the global mineral production, 80% is performed by surface mining methods (Younger, Banwart & Hedin 2002). Surface mining can be divided into mechanical excavation and aqueous excavation. The mechanical excavation class consists of open pit mining, quarrying and open-cast mining (Hartman & Mutmansky 2002). Aqueous extraction consists of all methods using water or a liquid solvent to recover minerals (Hartman & Mutmansky 2002) and can be further divided into the subclasses placer mining and solution mining methods (Hartman & Mutmansky 2002). In placer mining methods, water is used to excavate, transport and/or concentrate heavy minerals from alluvial or placer deposits. In solution mining, minerals that are soluble, fusible or easily recovered in slurry form are extracted, normally by using water or liquid solvents (Hartman & Mutmansky 2002).

Below, the most common methods for the extraction of copper, gold and uranium are treated more thoroughly.

4.1.1.1 Open-Pit Mining

Open-pit mining is used when the minerals occur near the surface (Aswathanarayana 2003). A surface pit is excavated, using one or several horizontal benches. For mining thick deposits, several

benches are excavated and form the pit walls like an inverted cone. The reason for using benches is that it enables control of the blast holes as well as the slope of the pit walls (Hartman & Mutmansky 2002).

For small open-pit mines, capital investments and running costs are low compared to underground mines of equal size. However, large open-pit mines require much more preproduction investments than comparable underground mines. Nevertheless, the running costs are still low for large open-pit mines and the mining rate can be extremely high. Furthermore, ores can be mined at a grade that is not economically feasible using other mining methods (Carr and Herz 1989).

The first step in open-pit mining is to expose the ore-body. This is achieved by stripping away the overburden from benches and ramps. The overburden is transported to dumps near the pit. Apart from handling equipment, economical characteristics and depth of the ore body as well as characteristics of the ore and overburden are examples of factors that decide the design of the pit (Carr and Herz 1989).

When removing the ore from the pit, holes are drilled into the bench and loaded with ANFO (ammonium nitrate-fuel oil mixture) explosive. Nitroglycerine-type explosives are also used but in smaller holes or for the blasting of incompletely broken material. After the blasting, the ore is transported on ramps or spiral roadways or, in some cases, by beltways or tunnels leading to the plant or dump site (Carr and Herz 1989).

4.1.1.2 Placer Mining

Placer mining is used for the mining of gravel and sand containing gold, tin, titanium and rare-earth minerals. Placer mining can be done by dry-land methods or by dredging. Dry-land placer mining is very similar to shallow open-cut mining and strip-mining, except that gravel banks can be removed by pressurised water stream (Carr and Herz 1989), undercutting and caving it (Hartman & Mutmansky 2002).

4.1.1.3 Leaching

Leaching is the chemical extraction of metals or minerals in the deposit or from material already mined. Bacteriological extraction also exists but is not as common. There are two variations of leaching, percolation leaching and flooded leaching. If the extraction is done within the confines of a deposit, it is called in situ leaching, which will be treated separately. Heap leaching is the method performed on already mined dumps, tailings or slag piles (Hartman & Mutmansky 2002).

4.1.2 Underground Mining

When ore veins are steep or deposits bedded, the costs of removing waste rock makes it impossible to use surface mining methods. Instead underground mining can be used. Commonly, surface mining methods are used to a certain depth until it is only economically feasible to continue excavations with underground mining (Carr and Herz 1989). Underground methods differ by the wall and roof support, the opening configuration and the direction of the extraction process. The alternative methods of underground mining are unsupported, supported and caving operations (Hartman and Mutmansky 2002).

The ore can be accessed by either a horizontal tunnel (adit), a vertical shaft sunk in the ore body or in solid rock near the ore body. It can also be accessed by a decline, by an inclined shaft or a gently

inclined access spiral. Rubber-tired trucks can then be used to haul material to the surface (Carr and Herz, 1989).

Underground mining operations generally follow a procedure of drilling, blasting, mucking (i.e. removal of broken rock) and the installations of ground support (timber or roof bolts) (Carr and Herz, 1989). Waste rock and broken ore is collected and transferred to different haulage units by air- or electric operated mechanical loaders, cable guided scraper systems or by mobile conveyors. Electric-, diesel- or compressed-air-powered locomotives with trains of ore cars are normally used for haulage to transfer points and the mine portal (Carr and Herz, 1989).

4.1.3 In Situ Leaching and Borehole Mining

In Situ leaching is a method using hydrometallurgy to recover copper, uranium and gold from mineral ore that is permeable in its natural state or is made permeable by e.g. explosive shattering, block caving or hydraulic fracturing (Carr and Herz 1989). The mine is composed of well fields that are established over the ore-body (Hore-Lacy 2004). Instead of removing the ore-body from the ground, a liquid is pumped through the ore, using the wells, dissolving the minerals (WNA: In Situ Leaching 2008). Initially, submersible pumps extract some of the native groundwater from the host aquifer and then a leach solution is added and injected into the well field. The pregnant solutions from the wells are pumped to the surface where the mineral is recovered in the same manner as for other mining methods (Hore-Lacy 2004).

The ISL process is more or less a reversed mineral ore genesis and it can be done by an alkali or acid solvent. What to use depends of the geology and the groundwater. If significant amounts of calcium (as limestone or gypsum) are contained in the ore-body, alkaline (carbonate) leaching must be used. This is the case for host aquifers in the US (WNA: In Situ Leaching 2008). Otherwise, acid leaching is generally better and is the method used in Canada and Australia. Therefore, the oxidant and complexity agents that are used differ in different locations and sites (Hore-Lacy 2004).

Positive aspects with ISL are that there is little surface disturbance and less waste generation but it is crucial that the ore-body is isolated so that the leaching solutions do not contaminate groundwater away from the ore-body. However, considering today's technology, ISL is regarded as a controllable and environmentally safe extraction method (Hore-Lacy 2004).

4.2 Beneficiation

The process of removing unwanted ore constituents in order to prepare it for subsequent processing stages is the beneficiation. Beneficiation is carried out in a mill, which is usually located near the mine site in order to reduce costs of transportation. Beneficiation consists of three stages: preparation, in which the ore is comminuted by crushing and grinding; concentration, in which the desired ore mineral is separated from gangue; and finally dewatering of the concentrate. Concentration can be performed in various ways: gravity separation, magnetic separation and flotation. Flotation is based on principles of surface chemistry and it uses a wide range of reagents. It is the most common method used for concentrating base metal sulphide ores (Ripley, Redman & Crowder 1996).

Crushing is performed in several stages until the ore is reduced to 5-25 mm size range. The following procedure is the grinding in which the grain size is further reduced. In order to optimise the

comminution process in terms of resource use and efficiency it is important to keep track of ore characteristics and adjust the process to suit the ore (Ripley, Redman & Crowder 1996).

The beneficiation stage results in atmospheric emissions mainly stemming from transportation, crushing and grinding of the ore and from dry separation methods. These emissions can largely be reduced by using closed process lines. In flotation however, the main emissions are hydrospheric in nature. Some reagents may be passed on to metallurgical stages as components of the concentrate while others may be transferred to the tailings in the bulk unless they are recycled (Ripley, Redman & Crowder 1996).

4.3 Metallurgical Processing and Refining

Metallurgical processing and refining embodies all the treatment of the ore after extraction and beneficiation. Contrary to earlier process steps, most of this treatment involves changes to the chemical nature of the mined minerals. The purpose of these processes, known as extractive metallurgy, is to isolate the metal from its mineral. Extractive metallurgy may be divided into three groups: pyrometallurgy, using high temperatures to initiate and sustain extractive reactions; hydrometallurgy, using liquid solvents to leach the desired metal from the ore; and electrometallurgy in which electrical energy is used to dissociate the metal in aqueous solution. Some metals are extracted by only one of these methods while others require combinations of two or several methods (Ripley, Redman & Crowder 1996).

Pyrometallurgy is the oldest form of extractive metallurgy and its purpose is to convert the metal from its sulphide or oxide form to a form closer to the pure element. It can be divided into four stages: preparatory treatment, smelting, converting and fire refining. Smelting is the most widely used pyrometallurgical process. Roasting, one preparatory treatment, burns off 20-50% of the sulphur content of the concentrate. The subsequent smelting produces a so called matte, which is approximately 50% pure. Both roasting and smelting release sulphur dioxide as flue gas. During the conversion, the remainder of the sulphur is oxidised with an excess of air or oxygen, raising the metal purity to about 98%. Normally, both slag, dust and fumes are recycled into the process feed in order to reduce loss of valuable materials and to minimise emissions. However, emissions of sulphur dioxide remain high. The converted metal may undergo fire refining, which further oxidises impurities reducing them to about a half of previous levels (Ripley, Redman & Crowder 1996, p. 35). Most of the ores processed by pyrometallurgy are sulphides containing both sulphur and iron, which are oxidised during the smelting process. Sulphur is emitted to air as sulphur dioxide and iron ends up in the slag in the form of iron oxide. Other emissions include particulates, which can be formed by metallic and non-metallic compounds (Ripley, Redman & Crowder 1996).

Contrary to pyrometallurgical processes, hydrometallurgy does not produce sulphur dioxide, which is an important environmental advantage. Water and aqueous solutions of acids and bases are the most common hydrometallurgical solvents. The process involves four steps: preparation phase, solution phase (leaching), solid liquid separation and treatment; and finally concentration and deposition of the metal bearing solution. Hydrometallurgy consumes large amounts of water and care must be taken to avoid contamination of effluent water (Ripley, Redman & Crowder 1996).

The use of electricity in the extraction of metals from their ores can be performed either by electrolysis or by electrothermal methods. Electrothermal methods are a form of pyrometallurgy, which compared with other pyrometallurgical methods have some advantages such as high

temperature capability, more accurate temperature control, no requirement of air to support combustion and greater thermal efficiency. Electrowinning, electrorefining and electroplating are different forms of electrolysis. In electrorefining, the impure metal acts as the anode and the pure metal is transferred via a solution of high electrical conductivity onto the cathode. In electrowinning, the metal to be purified is found in the electrolyte and the anodes are soluble. Electrowinning consumes much more energy per amount of product than electrorefining (Ripley, Redman & Crowder 1996).

5 Health and Environment in the Mining Industry

The following text will discuss environmental impacts and health aspects in the mining industry in general. Special attention will be given to the issues of tailings and radiation.

5.1 Environmental Impacts

Three main types of changes are distinguished as a result of mining: change in the natural topography which results in restrictions in the possibilities of using the land for other purposes, changes in the hydrogeological conditions with consequences for both groundwater and surface water and finally changes in the geotechnical conditions of the rock (Aswathanaryana 2003). The impact varies with local conditions of the specific site of mining. These changes caused by mining can give rise to various impacts on the geoenvironment, described below.

5.1.1 Impacts on the Lithosphere

Depending on the type of mining conducted and the site of mining there are several types of impacts on the lithosphere. The results range from formation of ridges, depressions, pits and subsidence on the surface as well as underground cavities affecting the stability of the ground. Furthermore, both the area for mining and the area used for waste dumps, occupy and degrade land that could be used for e.g. farming and agriculture (Aswathanaryana 2003).

5.1.2 Impacts on the Hydrosphere

Impacts on the hydrosphere resulting from mining include lowering of the groundwater table, mine water discharge into rivers, seas and lakes, leakage from settling tanks and evaporators that have a negative effect on the groundwater quality and pumping of water into the ground for the extraction of a mineral (Aswathanaryana 2003).

Significantly lowered groundwater levels can result in huge surface depressions and drained rivers and lakes with serious impacts on surrounding agriculture for example. Furthermore, depending on the chemical composition of the rock, the drained water usually becomes highly acidic with the resulting capability of taking into solution a variety of toxic and heavy metals (Aswathanaryana 2003).

5.1.3 Impacts on the Atmosphere

Atmospheric emissions during mining occur not only from internal combustion engines in mining machinery but dust and gases are also released from blasts and rocks and mineral masses. One tonne of explosives produces about 40-50 m³ nitrogen oxides and huge amounts of dust (Aswathanaryana 2003).

Smelters are commonly used for mineral purification and emissions from these processes include particulate matter and gases such as sulphur dioxide, carbon monoxide and carbon dioxide. Although some installations use different kinds of flue gas purifications, these are never completely effective (Carr & Herz eds. 1989).

5.1.4 Impacts on the Biosphere

The biosphere is adversely affected by mining mainly by pollution and by degradation of land and vegetation resulting in loss in biodiversity. Mining can also have impact on local microclimate (Aswathanaryana 2003).

5.2 Health Aspects

Mining is one of the most hazardous industrial occupations and during the period 1980-89, mining was the industry with the highest annual number of traumatic fatalities. Health impacts from mining can be divided into two categories: immediate impacts such as accidents; and accumulative and progressive impacts such as stress, radiation and pulmonary diseases (Aswathanaryana 2003). In terms of health hazards, four different types can be distinguished: physical, chemical, biological and mental hazards:

5.2.1 Physical Hazards

Physical hazards include noise, heat, vibrations, falls and explosions, flooding and various forms of dust, aerosols and fine particles with resulting fibrogenetic and carcinogenic effects (Aswathanaryana 2003). Ionizing radiation is included in the category of physical hazards.

5.2.2 Chemical Hazards

Chemical hazards arise from chemical pollutants in water, solid wastes and air with the most common substances being carbon monoxide and dioxide, oxides of sulphur, nitrogen oxides and fluorine compounds (Aswathanaryana 2003).

5.2.3 Biological Hazards

Biological hazards caused by living organisms such as fungus, bacteria and parasites are more common among mine workers in developing countries with poor standards of hygiene and sanitation.

5.2.4 Mental Hazards

Mental hazards involved with mining include claustrophobia, anxiety, tension or irritability involved with the awareness of the dangerous working site. Fatigue and other disorders linked to shift work are other potential problems among mine workers (Aswathanaryana 2003).

5.3 Tailings and Waste Rock

One of the most serious problems for the mining industry is the production of mine tailings, which annually amounts to 18 billion m³. That is more solid waste than generated by any other industry (Aswathanaryana 2003) and still, this figure is expected to double in the next 20-30 years as ores with progressively lower grades are being worked (Aswathanaryana 2003).

It is estimated that of all material excavated by mining operations, more than 70% is waste. Surface mining is the method that generates the most waste. At the beginning of the 21st Century, surface mining contributed to 80% of the global mineral production but to as much as 99% of all generated mine waste (Younger, Banwart & Hedin 2002).

Mine waste can be classified as waste rock or spoil and as tailings, also known as finings. Waste rock can arise during both the extraction and the processing of ore, while tailings are only generated

through processing. The fundamental difference between the two is that of the grain size. Waste rock is coarse-grained (1mm-50mm) and tailings can be characterized as fine grained (< 1mm) (Younger, Banwart & Hedin 2002). Furthermore, waste rock is normally tipped dry, while tailings are deposited from flowing water (Younger, Banwart & Hedin 2002).

When waste rock is not used as back-fill or used as bulk-fill in construction projects, it is stored in waste rock piles, generally formed by loose tipping from wagons or conveyor belts. Revegetation is currently common practice but until just recently, little has been done to the drainage to minimize leachate generation (Younger, Banwart & Hedin 2002).

Tailings used to be dumped in the nearest watercourse, until the early 20th Century, when it was discovered that this was not a sustainable behaviour. The original reason for abandoning this tailings management system was that the water routes required for shipping the products were obstructed. Today, tailings dams and tailings dykes constructed from waste rock and tailings material are generally used as storage facilities (Younger, Banwart & Hedin 2002).

The characteristics of the mine waste can be structured in different regions, where different processes are dominating. These regions are the source term, the near field and the far field. The source term is the actual waste dump, the near field deals with the treatment and management of the waste and the far field concerns different interactions between drainage water and the soil and water outside the constructed deposit (Höglund & Herbert eds. 2004). The terms are illustrated in Fig. 1.

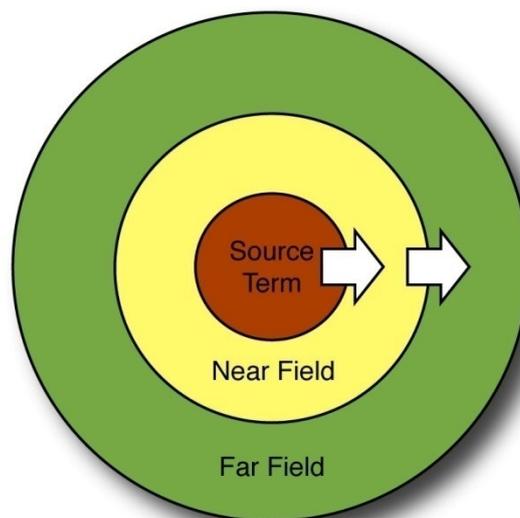


Fig. 1: Illustration of the dispersion of acidity and trace elements from the source term to the near field and far field (Adopted from Höglund & Herbert eds. (2004))

As suggested by Bert Allard¹, Professor in Chemistry and Project Manager for the Man-Technology-Environment (MTM) research centre at Örebro University, six analytical parameters related to the mine waste and important processes connected to the waste are described further:

¹ Bert Allard, Professor in Chemistry, Örebro University, meeting at Örebro University November 3, 2008

- The ore: source term and water chemistry
- Age of the operations
- Deposits management
- Metals and substances related to the different minerals and ores
- Process chemicals and complexes
- Geography: precipitation and hydrology

The ore is used as a take-off point and the remaining parameters are presented and further on discussed and compared in relation to the different types of ores of interest.

5.3.1 Source Term – Deposited Waste

The source term refers to the waste dump and characteristics that can be included are the total amounts of waste and the amounts as well as concentration of contaminants. Factors such as grain size, porosity and water retention properties, which are influencing the flow of oxygen and water through the deposits, are also of interest (Höglund & Herbert eds. 2004). In this report, however, the source term is limited to the amounts of waste produced and a basic composition of the tailings, excluding the concentrations of different contaminants.

5.3.1.1 Mineral Composition of Tailings

Copper is most commonly contained in copper-iron-sulphide (e.g. chalcopyrite (CuFeS_2) and bornite (Cu_5FeS_4)) and copper sulphide minerals (e.g. chalcocite (Cu_2S)). Also gold is often found associated with sulphides (Mindat.org: Gold 2008).

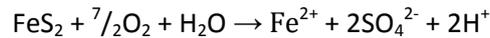
Oxides as pitchblende (Mindat.org: Pitchblende 2008) and secondary ores formed from pitchblende by weathering are the main uranium minerals (Metzler 2004), even if it can occur in sulphide minerals as well (Ripley, Redman & Crowder 1996).

The mineral composition of tailings is directly linked to the water quality of the tailings discharge. Reactions between minerals are dependent on tailings compositions and chemical properties of the water (pH, oxygen dissolved solutes etc) (Höglund & Herbert eds. 2004). When sulphides get in contact with water, the sulphide minerals are oxidized and sulphuric acid is produced, lowering pH of the water. This phenomenon, termed Acid Mine Drainage, AMD (Akcil & Koldas 2006), is further explained in the following section. Oxides are pH neutral¹ while carbonates have a buffering capacity (Höglund & Herbert eds. 2004) and constitute the most efficient minerals when it comes to neutralising acid from weathering sulphides (Envipro Miljöteknik AB 2006). Silicates are weathered when pH is lowered. Buffering silicates consume hydrogen ions when pH is low and can therefore counteract a further pH decrease (Höglund & Herbert eds. 2004).

5.3.1.2 Acid Mine Drainage

Generally, minerals that constitute economically valued ores are mostly stable under the reigning geological conditions in which they are found. When they are excavated and exposed to the atmosphere, they become less chemically stable. Sulphide minerals spontaneously dissolve in contact with water. The release of contaminants from ore and mine waste into hydrological cycles through chemical weathering makes potentially toxic solutes mobile and thus bio available. Metal ions and acidity are released by weathering of different sorts of sulphide ores (Younger, Banwart & Hedin 2002).

Pyrite (FeS₂) is one of the most common sulphide minerals and is therefore used as an example of oxidation of sulphide minerals (Akcil & Koldas 2006):



Oxygen oxidizes the sulphide mineral into dissolved iron, sulphate and hydrogen (Akcil & Koldas 2006). If the resulting sulphuric acid does not react with acid neutralising minerals such as calcite (Allard & Herbert 2006), it will induce a decrease in pH while total dissolved solids increase (Akcil & Koldas 2006). The ferrous ion Fe(II+) can be oxidised to ferric ion Fe(III+), which is itself a strong oxidant. The ferric ion can oxidise the sulphur and sulphide S(II-) in the sulphide minerals to sulphate SO₄²⁻ and will then be reduced again to ferrous ion (Allard & Herbert 2006, p. 22). For these reactions to occur, the pH must be low, between 2.3-3.5 (Akcil & Koldas 2006), otherwise the ferric ion will not be in solution but instead be precipitated as ferric oxyhydroxide (Allard & Herbert 2006).

The following chain of effects caused by AMD is mentioned by Young, Mulligan and Fukue (2007):

- Severe health threats to aquatic species, native habitat and plant life.
- Groundwater and drinking water pollution.
- Decline of soil quality.
- Release of heavy metals that are otherwise contained by soil.

Although the sulphide minerals only constitute a small fraction of the broken ore, it can create major environmental degradation lasting for decades or even centuries after mine closure (Younger, Banwart & Hedin 2002).

Several factors determine the extent of the acidic leachate generation at a mine site. These factors can be: the type and concentration of sulphide mineral in the host ore; spent ore and leach piles; type of host rock; the availability of oxygen; hydrogeology at the site; pH of the water in the system and finally; the presence (or absence) of bacteria (Young, Mulligan & Fukue 2007).

5.3.1.3 Age of Tailings

A prerequisite for the reaction described in the last section, where ferric ions acts as oxidants, causing a continued acidification, is the presence of iron in the tailings deposition. Today, the ore is processed to the extent that it is virtually free from iron. The same does not go for older process waste, unfortunately. Even though old tailings might have been covered to shield them from contact with oxygen, significant amounts of oxidised iron are most likely present in the waste dumps². If the pH drops, the ferric iron can dissolve and oxidise more of the sulphide minerals, hence decrease the pH. However, if pH is kept high, the ferric ion will not cause any problem but instead absorb many toxic metals in solution and decelerate their movement (Allard & Herbert 2006).

5.3.1.4 Metals and Substances of Importance

Consequences of iron in sulphide tailings have already been mentioned briefly. Other metals and substances that that are important to consider when dealing with these issues are heavy metals and uranium and its radon progenies.

² Bert Allard, Professor in Chemistry, Örebro University, meeting at Örebro University November 3, 2008

Heavy Metals

According to Young, Mulligan and Fukue (2007), common heavy metals that can be found in the geoenvironment are results of human activities (e.g. mining). The more notable and interesting metals for this study are those mostly connected to sulphide ores, and the acid mine drainage dilemma, namely arsenic (As), cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn) (Young, Mulligan & Fukue 2007). Copper needs no further presentation but the rest will be briefly introduced.

Arsenic is mostly found in iron ores and in sulphide form, the most common ores being, among others, arsenopyrite (FeAsS) and realgar (As₂S₃). Arsenic is a toxic element and most countries have adopted a regulatory limit of 50 µg/l in groundwater for drinking. Ingestion of arsenic can lead to e.g. death from hypertensive heart disease or skin diseases, such as keratosis and hyperpigmentation (Young, Mulligan & Fukue 2007).

Cadmium can be found as greenockite (cadmium sulphate CdS) and otavite (cadmium carbonate, CdCO₃) and is often associated with zinc, lead and copper in sulphide form (Young, Mulligan & Fukue 2007). Accumulation of orally ingested cadmium in the liver and kidney can cause organ distress and the threshold value for drinking water, given by the US Environmental Protection Agency is 5 ppb (Young, Mulligan & Fukue 2007).

Lead is in the nature found in sulphide minerals (galena, PbS and anglesite, PbSO₄), oxide minerals (minium, PbO) and carbonate minerals (cerrusite, PbCO₃) (Young, Mulligan & Fukue 2007). The central nervous system, kidneys and the reproduction systems can be affected by inhalation and ingestion of lead.

Zinc is mostly found as zinc compounds, in combination with oxides, sulphides and carbonates, of which the sulphide form is probably the most common one. Zinc is often associated with cadmium, even if zinc is not as toxic (Young, Mulligan & Fukue 2007).

Uranium and Radon Progenies

Mining and milling of uranium can potentially result in residuals like waste rock and tailings, liquid pollutants and particulate and gaseous emissions to the atmosphere, just as in the case for other mining operations. However, uranium mining is significantly different in terms of health and environmental prerequisites since the mined rock and the resulting mine waste can contain radioactive materials. Radionuclides from the uranium decay chain such as radium, thorium and their decay products; ²¹⁰Pb, ²¹⁰Po and ²³⁰Th are some of the most potentially harmful substances associated with uranium mining. Furthermore, radon or rather the presence of its radon progenies which are radioactive solids that can be ingested or inhaled are other sources of concern in the uranium mining industry. These kinds of issues are mainly occupational hazard for people working at the uranium mine and mill and for people, animals and plants living in the vicinities of mines, mills, waste rock or tailings (Ripley, Redman & Crowder 1996).

5.3.2 Near Field – Prevention and Control Methods

The near field includes all the aspects of the wastes deposits and the engineered barriers and control measures (Höglund & Herbert eds. 2004). Many aspects have to be considered for successful management and remediation of tailings.

Waste deposits management has primarily been focused at lasting re-vegetation of spoil and the prevention of the release of polluting leachates from the spoil materials (Younger, Banwart & Hedin 2002). The type of waste in the deposit determines what issues to address and how they should be dealt with.

5.3.2.1 *Managing Acid Mine Drainage*

The main process driving chemical changes in waste deposits from sulphide ore processing is the intrusion of oxygen (Moreno & Neretnieks 2006). By decreasing the oxidation caused by oxygen, the potential environmental loads are decreased as well and the soil and ground have a better chance of buffering and neutralising the effects of the recipients. This can be done by either covering the tailings with soil or water, two techniques that are considered the best available by EU. Which one of the two that is the most appropriate method depends on site-specific characteristics (Höglund & Herbert eds. 2004).

Soil covers constrain the oxygen flux in the tailings and can therefore prevent weathering of sulphides. However, for succeeding with the method, appropriate soil qualities for the cover are needed, enabling a maintained water balance for a long period of time. The soil cover should be able to sustain high water saturation. Beside particle sizes in the soil, the degree of compaction is an important factor, not only for the hydraulic conductivity of the sealing layer but additionally for preventing roots from penetrating the cover, creating macro pores that can enhance oxygen diffusion.

Finally, the soil cover also has to be protected from erosion by heavy rainfalls and snowmelt (Höglund & Herbert eds. 2004) by runoffs, leading the large amounts of water from the top of the impoundment. The transportation and control of groundwater is another critical issue (Höglund & Herbert eds. 2004).

The oxygen diffusion rate in saturated tailings water is about 10000 times slower than in air. Hence, the second technique, water cover, can be useful against oxygen intrusion. For this method to work, the water must be stagnant and not allowed to be mixed. As well, freshwater containing oxygen needs to be shielded from the tailings (Höglund & Herbert eds. 2004), including groundwater.

5.3.2.2 *Uranium Tailings Management*

About 85% of the radioactive material in the broken ore is discharged with the mill-tailings slurry and the major risk of losses of solid materials from these wastes is associated with wind and water erosion. For these reasons, a proper containment of tailings is the most important aspect in terms of long term reduction of radiological and chemical pollution from uranium mining and some claim that continuous improvement in these issues has resulted in uranium tailings being better managed than those of other mining sectors. Open pit mines generally produce more particulate emissions than underground operations due to their exposure to wind and rain (Ripley, Redman & Crowder 1996).

To deal with radon and radioactivity, uranium tailings are often covered by water. During decommissioning, a couple of metres of clay and top soil are normally used to cover the waste to reduce the radiation levels (WNA: Environmental Aspects of Uranium Mining 2008). Re-vegetation is often recommended, in order to prevent erosion. However, potential transfers of radioactive material might be caused by the vegetation and have to be considered carefully. Radioactive material can be brought to the ground via the roots of vegetation and made available for feeding animals.

Plants can also accumulate airborne radioactive materials that consequently become available for herbivores. Finally, radon that is sufficient soluble to move up the plant with the transpiration stream, can be released from the leaves of the plants. Plants with small leaf surfaces and shallow root systems that are not palatable to animals, should be used when re-vegetating uranium waste deposits (Ripley, Redman & Crowder 1996).

5.3.2.3 Process Chemicals and Transporters of Heavy Metals

There are a number of chemicals and processes that contribute to the transportation of toxic metals and substances connected to tailings and waste management. Sulphuric acid is a commonly used leaching chemical, used in e.g. uranium mining (Hore-Lacy 2004) but also when processing copper in oxide ores (Davenport et al. 2002). Acidic leaching chemicals can be neutralized and is therefore not discussed further (Hartman & Mutmanský, 2002). When extracting copper from the grinded and milled ore, this is often done by flotation and thus by using a number of flotation chemicals. It is reasonable to assume that the flotation chemicals affect the effluents in some way. The chemicals used differ and what is used in the specific operations is unknown and hence, so is also the extent to which they affect the effluents and surrounding.

Cyanide

Besides acid mine drainage of gold tailings connected to sulphide ores, the most toxic remainder from lode gold mining is cyanide (Ripley, Redman & Crowder 1996).

The most problematic form of cyanide is free cyanide that includes the cyanide anion and hydrogen cyanide, HCN (ICMI: Environmental and Health Effects of Cyanide 2006). Cyanide is very reactive and forms simple salts with alkali cations and ionic complexes with metal cations. The strength of the ionic complexes can vary. Weak-acid-dissociables (WAD) are weak or moderately stable complexes of e.g. cadmium, copper and zinc, that are less toxic than free cyanide (ICMI: Cyanide Chemistry 2006). Nevertheless, under varying environmental conditions such as ingestion and absorption by wildlife, the dissolutions can release free cyanide as well as potentially toxic metal-ions. Cyanide can also form very stable complexes with gold, lead, cobalt and mercury (Donato et al 2006).

The different types of cyanide commonly present in the tailings dams are free cyanide, WAD cyanide and total cyanides. Free cyanide is not persistent in the tailings and will decay through different processes to less toxic chemicals. The WAD cyanide on the other hand is persistent and can release cyanide when for example being ingested as mentioned above (Donato et al 2006).

Cyanide salts and complexes stability is pH dependent and given that the bioavailable toxicity of cyanide depends on the types of complexes present, the environmental impacts of cyanide contamination can vary (ICMI: Cyanide Chemistry 2006). Still, cyano-compounds that liberate free cyanide ions are highly toxic to almost all forms of flora and fauna (Souren 2000 see Donato 2007). Cyanide is a fast acting poison. Poisoning of biota may occur by inhalation of dust, ingestion and absorption through mucous membranes or through direct contact with skin. Cyanide binds to enzymes and proteins containing iron, copper or sulphur, that are needed for the transportation of oxygen to cells. This leads to cell death. In higher animals, the most affected organ is the brain, resulting in coma and collapse of the respiratory and cardiovascular system (Donato et al 2007). In a tailings environment, the species with the highest risks of contamination are those that drink, feed or roost on habitats around cyanide bearing tailings systems (Donato et al 2007). This aspect is

especially serious in dry climates where animals are attracted to the water in tailings impoundments (Balkau 1998).

Cyanide is a non-selective solvent and can therefore bring several hazardous substances in solution (Ripley, Redman and Crowder 1996). When forming complexes with other metals from the ore, e.g. copper and iron, cyanide is not available for dissolving the gold (ICMI: Cyanide Chemistry 2006). Gold recovery from sulphide minerals requires additional amounts of cyanide to compensate for decreased gold recovery rates due to the fact that the cyanide leach the sulphide minerals before the gold (ICMI: Use of Cyanide in the Gold Industry 2006). In an environmental context the copper content is of great interest as well, since copper-cyanide complexes are toxic to birds and bats (Donato et al 2006).

Organic Material and Carbonates

Natural organic matter (NOM) is an important part of surface water biogeochemistry as well as of reactions in the soil. Not only can NOM buffer pH in the range of weak acids, but it is also able to form complexes with metal ions in solution, decreasing their transportation ability. Humic substances are important with respect to these characteristics of NOM (Höglund & Herbert eds. 2004). However, the organic content of tailings is in general very low (Höglund & Herbert eds. 2004).

Carbonates are the most efficient minerals when it comes to neutralising acid from weathering sulphides (Envipro Miljöteknik AB), and carbonate ions are also able to slow down the transportation of heavy metals from tailings water by the precipitation of carbonates. If the concentrations of metal ions and carbonate ions are sufficiently high, these will react and form carbonates. However, to maintain surplus concentrations of carbonate ions, pH levels cannot be too low (Berggren et al 2006).

5.3.3 Far Field

This perspective includes the area receiving the drainage water from the tailings deposit and is of great importance to understand the consequences and environmental impacts caused by the tailings (Höglund & Herbert eds. 2004).

5.3.3.1 Geography

Water and oxygen is of great importance for acid mine drainage. Flow direction, residence time and groundwater levels and properties of surface waters are all of interest for the estimations of the transport and spreading of contaminants (Allard & Herbert 2006). Therefore, the climate, landscape scene and hydrological properties of the soil are examples of crucial aspects. A dry area will not have the same problems with acid mine drainage as an area with much precipitation due to lower rates of weathering of sulphide minerals. Similarly, water access differs between an operation situated on the top of a hill and a site in a valley.

5.4 Rehabilitation of Mined Land

Mining operations affect the land in several different respects. It deforms the landscape and can for example cause landslides, pollution of water and soil, lowering of groundwater levels etc. Mining companies are today required to include rehabilitation plans and funds in the decommissioning procedures of a mine. Restoration aims at restoring the productivity of the affected land area, harmonize the landscape and reduce the risk of further land degradation. It involves landscaping and revegetating of spoil heaps, pits, disused industrial areas etc. What rehabilitation procedure to use

depends on factors such as mining methods, climate, soil and hydrology as well as the intended reason for the restoration (Aswathanarayana 2003). Despite all the various aspects influencing the restoration activities, Aswathanarayana (2003) lists a number of elements that are common for rehabilitation procedures:

- Removal and retention from topsoil that can be spread in the area of rehabilitation.
- Reshaping the degraded areas and waste dumps for them to be stable, well drained, and suitably landscaped for the desired long-term use.
- Minimizing the potentiality of wind and water erosion.
- Deep ripping of the compacted surface.
- Revegetation in order to control erosion and facilitate the development of a stable ecosystem compatible with the projected long-term use.

In general, open pits are harmonized with its surroundings or filled up for new land use options. In the past, pits have often been used for waste storage, but this is not common practice anymore due to problems with water leachates and succeeding risk of groundwater contamination. Instead, pits can be filled with water, preventing the mineral from being exposed to oxygen and by that avoiding chemical weathering (see chapter 5.3.2.1 Managing acid mine drainage). The resulting artificial lake can additionally be an asset for the near area. Another alternative is to seal the pit against seepage and in that way reduce the acid mine drainage problems (Fukue et al 2007).

Apart from groundwater considerations, the rehabilitation of ISL mines is less dramatic. The wells are sealed and capped, process facilities moved and evaporation ponds, if existing, are revegetated (Hore-Lacy 2004).

The combination of economics (rehabilitation expenditures versus income from new vegetation) and social priorities together with government regulations often decide the ambitions of restorations (Aswathanarayana 2003).

5.5 Ionizing Radiation

Mining of uranium is unique compared to the mining of other minerals since the mineral extracted can cause short-term and long-term damage to biological tissues due to its ability to emit ionizing radiation (Ripley, Redman & Crowder 1996). This one but significant difference in the prerequisites of the analysed objects deserves to be developed further.

5.5.1 Nature and Types of Ionizing Radiation

Radiation is the process of emitting radiant energy in the form of waves or particles. Ionizing radiation refers to radiation that has the ability to remove electrons from the material absorbing the radiant energy, thus producing ions. Ionizing radiation is produced by the nuclear disintegration of a radioactive material but it can also be formed from other sources. The activity of a radioactive material is measured by the number of nuclear disintegrations per unit of time expressed in the unit Becquerel (Bq). One Becquerel is one disintegration per second (Ripley, Redman & Crowder 1996). The decay of different unstable isotopes gives rise to different types of radiation with varying effects on biological tissues.

Alpha radiation consists of helium nuclei and because of its relatively large size it can be screened by thin material such as the skin or a piece of paper. Alpha radiation emitting isotopes are generally

considered to be a hazard only if ingested or inhaled (Ripley, Redman & Crowder 1996). Radon, which is a gas produced from the radioactive decay of uranium, has decay products or so called radon daughters that are alpha-emitters. Due to the gaseous nature of radon, it, or radon daughters attached to dust particles, can be inhaled and radon daughters can be formed in the body, where they constitute a significant hazard. Beta radiation consists of fast moving electrons and it can penetrate a little way into tissues but it is easily shielded by a few millimetres of wood for example. If kept in appropriate sealed containers, beta-radioactive substances generally pose no harm to humans. Gamma rays are electromagnetic radiation of high energy requiring more significant shielding (WNA: Radiation and Nuclear Energy 2007). Shielding by several centimetres of lead, decimetres of concrete or metres of water is required to block gamma radiation (SSM 2008).

Other types of ionizing radiation include X-rays, cosmic radiation from outer space consisting mostly of protons, and neutrons, which mainly originates from nuclear fission (WNA: Radiation and Nuclear Energy 2007).

5.5.2 Doses of Ionizing Radiation

The amount of radiation energy absorbed by biological tissues is measured in Gray (Gy), where 1 Gray represents the deposition of one joule of energy per kilogram of tissue. Since different types of radiation have different effects in different types of biological tissues, the unit Sievert (Sv) is used to quantify the total dose received by an individual. This unit takes into account both the amount and type of radiation and the relative sensitivity to radiation of the tissue receiving the dose. For practical purposes, doses to humans are mostly measured in millisieverts (mSv) (WNA: Radiation and Nuclear Energy 2007).

According to recommendations of the International Commission on Radiological Protection, ICRP, the above background radiation dose limits for application in occupational exposure are set to a maximum of 100 mSv over a period of five years on the further provision that the average dose received during one year does not exceed 50 mSv (ICRP 1991).

Worldwide average background radiation dose is estimated to be 2.4 mSv per year and more than half of this radiation originates from inhalation exposure from radon (The National Academies 2006). In certain areas in the city of Ramsar in northern Iran, annual background radiation doses amount to 260 mSv (Ghiassi-Nejad et al 2002). Single doses of about 5000 mSv are considered to be fatal for half of the exposed population and single doses of 10000 mSv are lethal within weeks (WNA: Radiation and Nuclear Energy 2007).

Occupational radiation doses reported by the investigated objects range from averages below 1 mSv per year to maximum doses on single individuals of just below 13 mSv per year. Doses below 100 mSv are defined as low-level doses (The National Academies 2006). The total effective dose normally reported in the mines is the sum of the contributions including gamma, radon progeny and long lived radioactive dust (AREVA Resources Canada Inc. 2008).

When comparing total average occupational radiation exposures however, workers in the mining industry with an average effective dose of 2.7 mSv per year receive lower doses than for example air travel crew (3.0 mSv/year) and above ground workplaces (4.8 mSv/year) (UNSCEAR 2006).

Anxiety about health aspects connected to the mine operations from people residing in the vicinity of the mines is not uncommon. The mines often conduct monitoring of certain parameters, such as radionuclide concentrations and radon levels, around the sites. Based on the obtained data, doses to

the public are calculated. At the investigated sites, doses to the public contributed by the operations range from 0.003 to 0.1 mSv per year. This means that some levels above background radiation are below detection limits.

5.5.3 Exposure Pathways of Ionizing Radiation

Doses of ionizing radiation are calculated values based on assessments using models of often very high complexity. The first step in the approach of assessing doses of ionizing radiation is to estimate the nature and magnitude of discharges of radioactive material into the environment. The emissions of radioactive substances result in elevated concentrations of these substances in air, water and soil and consequently also in terrestrial and aquatic foods (IAEA 2001). Concentrations can be obtained either by modelling or by measurements (ICRP 2006). Based on this information, the absorbed dose is calculated for a specified individual or group of individuals. The procedure is outlined in Fig. 2.

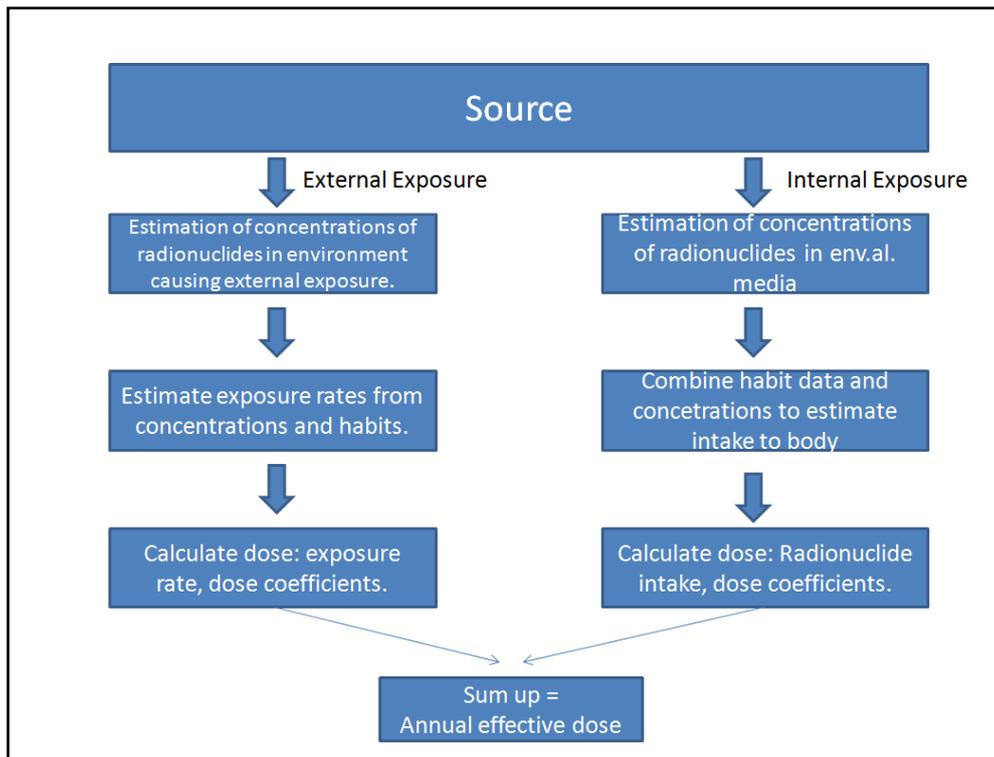


Fig. 2: Dose assessment process (adopted from ICRP (2006)).

The estimated doses are calculated for what is called a representative person, which is a hypothetical construction of the more highly exposed individuals in the population. When considering doses to the representative person, the following factors are taken into account: relevant pathways of exposure, spatial distributions of radionuclides in the region assessed, habit data for the specific population and different dose coefficients for specific age categories (ICRP 2006).

5.5.4 Health Impacts from Ionizing Radiation

The mechanisms behind the occurrence of adverse health effects in individuals exposed to ionizing radiation are not fully understood. Risk models assessing risks associated with exposure to ionizing radiation are based on epidemiologic studies of groups of populations that have received doses of radiation. Survivors of the Hiroshima and Nagasaki atomic bombings are the most thoroughly studied individuals for the evaluation of health effects of ionizing radiation. Other investigated groups

include persons that have been exposed because of medical reasons and nuclear workers (The National Academies 2006).

Ionizing radiation has the capability to change the structure of molecules and DNA within the cells of living tissues. If these changes cannot be repaired correctly, the affected cells can develop into potential cancer cells. Scientific evidence suggests that there is a linear relationship between the absorbed dose and the development of cancers in humans and that there is no threshold dose level below which the risk of developing cancers is not affected. Consequently, even very low doses of ionizing radiation result in slightly increased risks of developing cancer. This is the so-called linear-no-threshold (LNT) model. The BEIR VII report by the National Academies (2006) predicts that there is a one percent chance of developing cancer from a lifetime dose of 100 mSv and a 42 percent chance of developing cancer from other causes. When dealing with lower doses, it is expected that one in 1000 individuals would develop cancer from a dose of 10 mSv (The National Academies 2006). Exposure to an acute dose of 1 Sv is estimated to increase the lifetime risk of death from any form of cancer by 4.3 to 7.2 percent (UNSCEAR 2006). Increased risks of being affected by adverse health effects other than cancer from radiation exposure have been observed. Particularly cardiovascular diseases have been observed in individuals exposed to high or medium level doses. Increased risks of cardiovascular diseases in low-level radiation groups have not been observed (The National Academies 2006). Furthermore, factors such as gender, age at exposure and time since exposure influences the effects of ionizing radiation (UNSCEAR 2006).

Concern has been given to the contingent health hazards connected with living in the vicinity of uranium mines. Bollhöfer et al. (2006) have investigated concentrations of lead isotopes around the Ranger mine and their results show that the relative contribution from the mine to the airborne lead levels in the region was 13%. This was estimated to contribute to 40% of the total long-lived alpha activity in the region and that the dose received by people from this source was approximately 0.002 mSv per year. This is well below the public dose limit of 1 mSv per year (Bollhöfer et al. 2006).

A similar study by Tripathi et al. (2008) around the uranium mining, processing and tailings management facility at Jaduguda, India also concludes that radiation levels and radionuclide concentrations within a distance of five kilometres away from the site are marginally higher than elsewhere in the region. This includes radiation levels in surface water, ground water, soil and air.

6 Investigated Minerals

The investigated minerals in this study are all metallic minerals from three different categories. Gold is a precious metal, copper is a non ferrous metal within the sub group base metals and uranium belongs to the category of radioactive elements (Aswathanaryana 2003).

6.1 Uranium

Uranium is a naturally occurring element that can be found in approximately 50 minerals (Metzler 2004) and traces of uranium can be found in almost all natural materials (Carr and Herz, 1989).

Ore grades are commonly expressed in terms of uranium content or by their equivalent content of triuranium octoxide, U_3O_8 (Ripley, Redman & Crowder 1996) and the average crustal abundance is between 2 to 4 parts per million (Metzler 2005). Economic deposits have concentrations of about 0.1% (Aswathanaryana 2003) and can only be found in limited areas (Carr and Herz, 1989). Among the main uranium ores are uranite, also called pitchblende, carnotite, a uranium and vanadium mineral, and secondary minerals formed by weathering (Metzler 2004).

Uranium consists of three semi stable radioactive isotopes, namely Uranium-238, Uranium-235 and Uranium-234 (Carr and Herz, 1989). More than 99% of the naturally occurring uranium is ^{238}U and 0.71% of it is ^{235}U (Metzler, 2004). ^{235}U is the only fissionable of these uranium isotopes and for the uranium to be useful in a commercial nuclear power plant the share of ^{235}U has to be increased. The uranium is therefore enriched to normally 3-5% ^{235}U (McFarlane 2004). Hence significant amounts of ore have to be mined and processed to cover the current usage of uranium of approximately 65000 tU/year (WNA: Supply of Uranium 2008).

6.1.1 World Uranium Mining

More than 50 percent of the world's uranium comes from Canada (23%), Australia (21%) and Kazakhstan (16%). In 2007, underground mining made up half of the total uranium production. The second largest mining method was in situ leaching, comprising 29%. The largest companies are listed in *Tab. 1* below (WNA: World Uranium Mining 2008).

Company	tonnes U	%
Cameco	7 770	19
Rio Tinto	7 172	17
Areva	6 046	15
KazAtomProm	4 795	12
ARMZ	3 413	8
BHP Billiton	3 388	8
Navoi	2 320	6
Uranium One	784	2
GA/ Heathgate	673	2
Other	4 919	12
Total	41 279	100%

Tab. 1: The seven companies marketing the most of the uranium production (85%) in 2007 (adopted from WNA (World Uranium Mining 2008)).

6.1.2 Uranium Mining and Extraction

Generally, uranium mining does not differ from the mining of other minerals, unless the ore is of a very high uranium grade. Ore bodies close to the surface are mined by open-cut mining and when the deposit is deeper down, underground-mining methods are used instead (Hore-Lacy 2004). Deposits lying in groundwater in porous material are generally mined using in situ leaching (Hore-Lacy 2004).

To separate the uranium from the conventional hard rock mined mineral, the ore is crushed and grinded, normally under water to avoid dust (SKI 2006) and at some sites, it is performed underground (Hore-Lacy 2004). The result is a slurry of fine ore particles, mainly UO_3 and UO_2 , floating in water (Hore-Lacy 2004). Just like the process of ISL mining, the slurry is leached with sulphuric acid or carbonate leaching, with the help of an oxidant like hydroxide peroxide or ferric iron (Hore-Lacy 2004). In some cases, physical separation methods using the mass differences of the compounds (e.g. gravity concentration or flotation) can be used in combination with the leaching process (SKI 2006).

The liquid from the leaching containing the uranium is filtered and the uranium is separated from the solvent and minerals still present (Hore-Lacy 2004, p. 320). If the leaching of the minerals has been made with sodium carbonate and the solution is virtually free from other minerals, it is possible to separate the uranium by precipitating the carbonate solution using sodium hydroxide (SKI 2006). If sulphuric acid leaching has been used, the separation is instead performed by the use of ion exchange. The two methods used for ion exchange of uranium solutions are solid ion exchange with resin and liquid ion exchange using amines in kerosene. The latter, also known as solvent extraction, is today the predominate method (Hore-Lacy 2004). In solvent extraction, organic molecules in organic solutions bond to the specific targeted metal. Given that the organic solution and acidic solution cannot mix, the metal can be separated from the other metals still in the acidic solution (SKI 2006). The solvents are then stripped in a counter current process, where an ammonia sulphate solution is being used in the same time as gaseous ammonia is added, raising the pH, and yellow ammonium diuranate is precipitated. The diuranate is dewatered in a thickener, followed by a filter or centrifuge. Finally the diuranate is roasted in a furnace, producing the uranium oxide concentrate, also called yellow cake due to its colour (Hore-Lacy 2004).

6.2 Copper

One of the earliest metals used by man was copper. The reasons for this are numerous; it is found in mineral deposits in many areas around the world, both as a native metal and in minerals easily smelted to obtain the metal. Furthermore, it is easily worked, it has an attractive colour and a high resistance to corrosion. Apart from the above mentioned, its high thermal and electrical conductivity are characteristics that make the metal popular in the industrial era and about 50% of the production enters the electrical industry (Carr & Herz eds. 1989).

The continental crustal abundance of copper is around 47 ppm (Aswathanaryana 2003) and copper ores typically contain from 0.5% copper in open pit mines to 1 or 2% copper in underground mines (Davenport et al. 2002). Copper is mainly found in the crust in the form of copper-iron-sulphide (e.g. chalcopyrite (CuFeS_2) and bornite (Cu_5FeS_4)) and copper sulphide minerals (e.g. chalcocite (Cu_2S)) and also to a lesser extent as oxidised minerals such as carbonates, hydroxyl-silicates and sulphates.

Another source of increasing importance is recycled copper, which currently makes up between 10 to 15% of mine production (Davenport et al. 2002).

In the case of large near surface deposits, copper is extracted from open pit mines. When the overburden of the ore is impossible to strip, the ore is broken in underground mines (Carr & Herz eds. 1989). The total world production of copper in 1999 was 13200 ktonnes (Davenport et al. 2002) and Chile is by far the world's largest producer. It is estimated that nearly half of the world's mined copper comes from the Andes of South America (Davenport et al. 2002).

Depending on the type of broken ore, copper is refined in various ways. The two main extractive methods for refining copper ores are pyrometallurgical and hydrometallurgical methods. Copper-iron-sulphide ores make up about 80% of the world production. The ore has low solubility in aqueous solutions why pyrometallurgical methods have to be used to refine the ore (Davenport et al. 2002). This purification method involves the following steps:

Comminution (crushing and grinding) of the ore into finer particles (Davenport et al. 2002).

Concentration of the mineral particles by froth flotation. This is a method in which copper minerals are selectively attached to air bubbles rising through a water suspension containing the finely ground ore. Selectivity is achieved by adding reagents making the copper minerals hydrophobic. The resulting floated copper-mineral particles have a Cu concentration of about 30% (Davenport et al. 2002).

The flotation concentrate is consequently smelted in furnaces with oxygen-enriched air to oxidise sulphur and iron from the concentrate. The product is a copper-enriched molten sulphide phase called matte with a Cu concentration of 45 to 75%. This is a process generating large amounts of SO₂ in the off gas (Davenport et al. 2002).

The matte is further converted by oxidation in oxygen-enriched air. The heat generated by the oxidation of iron and sulphur is enough to make the process auto thermal. The product of the converting process is crude molten "blister" copper with a Cu concentration of 99% (Davenport et al. 2002). In some cases, smelting and converting are performed as one step. A major problem with this method however, is the high content (12-24%) of rejected oxidised copper in the slag (Davenport et al. 2002).

Finally, the "blister" copper is electrorefined to produce copper cathodes with less than 20 ppm undesirable impurities. To allow for electro refining, the blister copper is fire refined to produce impure copper anodes that are dissolved in an electrolyte containing copper sulphate and sulphuric acid (Davenport et al. 2002).

For oxide copper minerals and chalcocite ores, copper is refined with hydrometallurgical extraction. In this process, copper is leached from broken or crushed ore with sulphuric acid. Pure electrolyte is produced from the leaching solution by solvent extraction and the pure electrolyte is used to electroplate pure copper cathodes (Davenport et al. 2002).

6.3 Gold

Gold has, since being used as currency from around 1000 BC, played an important role as a valuable standard used to compare various currencies. Furthermore, apart from its attractive appearance making it suitable for decorative purposes and jewellery, it has found an increasing use in

technological applications due to its high malleability, conductivity and resistance to corrosion (Carr & Herz eds. 1989).

The average crustal abundance of gold is 0.005 g per tonne, which is much lower than for most other metals, for example silver (0.07 g/t) and copper (50 g/t). Gold occurs mainly in two ionic forms, Au^+ and Au^{3+} , which can form a series of complex ions that are important for transporting gold in natural environments (Carr & Herz eds. 1989). Native gold contains a few percent silver and alloys with silver, copper and platinoid metals often occur (Carr & Herz eds. 1989). In order to obtain commercial concentrations in ore however, the average crustal abundance must be upgraded by a factor of 3000 to 4000. This can occur by several natural processes involving for example gravity, leaching with natural fluids followed by redeposition in a more concentrated form (Marsden 2006).

Gold can be mined in various mines: primary gold mines, placer mining operations and in base metal mines (Ripley, Redman & Crowder 1996). About 10% of gold production originates from base metal mining such as copper (Ripley, Redman & Crowder 1996).

Lode ore deposits are normally mined with underground methods, which are more specific than open pit operations (Ripley, Redman & Crowder 1996).

Purification of gold from ores involves several stages and methods differ depending on the type of ore mined (Ripley, Redman & Crowder 1996). There are several different factors influencing the process selection in gold extraction. The factors can be categorised into six main areas: geological, mineralogical, metallurgical, environmental, geographical, economic and political. The process in which the gold ore is purified into pure gold involves the following unit processes: comminution, classification, solid-liquid separation, ore concentration, oxidative pre-treatment, leaching, solution purification and concentration, recovery, refining and effluent treatment (Marsden 2006).

Comminution of ore into smaller particles is performed in order to make the ore amenable to consecutive steps of gold extraction (Marsden 2006).

Classification, allows for selection of desirable particle size in various process steps. This is normally achieved with the aid of cyclones or screens within grinding circuits (Marsden 2006).

Solid-liquid separation allows for separation between different processes phases in various ways. Thickeners and filters are examples of the type of equipment used in solid-liquid separation and especially thickeners also provide valuable retention time for chemical reactions (Marsden 2006).

Ore concentration is performed to upgrade the ore in order to reduce costs and process volumes in subsequent process steps. The cost savings achieved by treating a smaller volume of material after ore concentration must be outweighed by the loss of valuable material in the rejected fraction. Ore sorting, gravity concentration, flotation, amalgamation, coal-gold agglomeration, electrostatic separation and magnetic separation are different methods of ore concentration (Marsden 2006). Gravity concentration and other ore concentration methods are used to remove larger gold particles from the crushed and grinded ore. The product is sent directly to refining whilst the remaining ore, after being recircled to crushing and grinding and gravity concentrator, is thickened and sent to the cyanidation process (Ripley, Redman & Crowder 1996). Among the concentration methods, amalgamation has been widely discussed due to the concerns over the health hazards associated with the use of mercury (Marsden 2006). Mercury forms an amalgam with any gold and silver present in the ore. In order to purify the gold from the amalgam, the mercury must be volatilized, a process in which about 10% of the mercury used is lost to the atmosphere (Ripley, Redman &

Crowder 1996). This has led to reduced use of amalgamation in industry but it is still used in some applications because of few suitable alternatives, especially in emerging and/or lesser-developed countries. Placer ore concentrates are generally best treated with mercury (Marsden 2006). However, the most important atmospheric emissions from lode gold mining occur when roasting some types of ores in order to remove sulphur compounds (Ripley, Redman & Crowder 1996).

Certain types of ores may require oxidative pre-treatment before undergoing conventional leaching. This step oxidizes the minerals in the ore in order to make it amenable to cyanide leaching. This pre-treatment can either be hydrometallurgical or pyrometallurgical. Worth mentioning among the hydrometallurgical methods are, pressure oxidation, which is both efficient and beneficial from an environmental point of view although both capital and operating costs are rather high, and biological oxidation with naturally occurring bacteria which can be a suitable but also rather slow process for certain types of ores. Roasting, a pyrometallurgical method has been used successfully on a wide range of ores for over 100 years. However, large quantities of gaseous effluents containing pollutants such as sulphur dioxide and arsenic trioxide are emitted in this process, which probably will lead to a decline in the application of roasting gold ores (Marsden 2006).

The following step in the purification of gold ores is leaching, a process in which the resulting product is a gold bearing solution. Gold ore is currently exclusively leached with dilute alkaline cyanide solutions, despite concerns over the toxicity of cyanide (Marsden 2006). The cyanide dissolves the gold and a number of potentially hazardous substances from the ore, and cyanide is usually the most important toxic remainder from lode gold mining (Ripley, Redman & Crowder 1996).

The leaching solution is subsequently purified and sometimes also concentrated before the gold is recovered in reduction processes, either chemically, by zinc precipitation or cementation, or electrolytically by electrowinning (Marsden 2006).

Refining is the step in which the final product, doré bullion with a precious metal content ranging from 90 to 99% is obtained by smelting what is obtained in the recovery process (Marsden 2006). Bullion can be refined further depending on the final use.

Finally, the waste products generated in all phases must be treated in an economic and environmentally acceptable manner. Treatment of waste products may be conducted both to detoxify a particular reagent but also to recover valuable elements from the waste stream. Generally, recovery of valuable constituents in the waste flow is conducted by either recycling all or parts of the waste flow back into previous processes or by treating the effluent in a dedicated process (Marsden 2006).

7 Investigated Mines

The following text will present the mines that constitute the core of the study. Their locations are indicated in *Fig. 3* and the operations are summarised in *Tab. 2*.

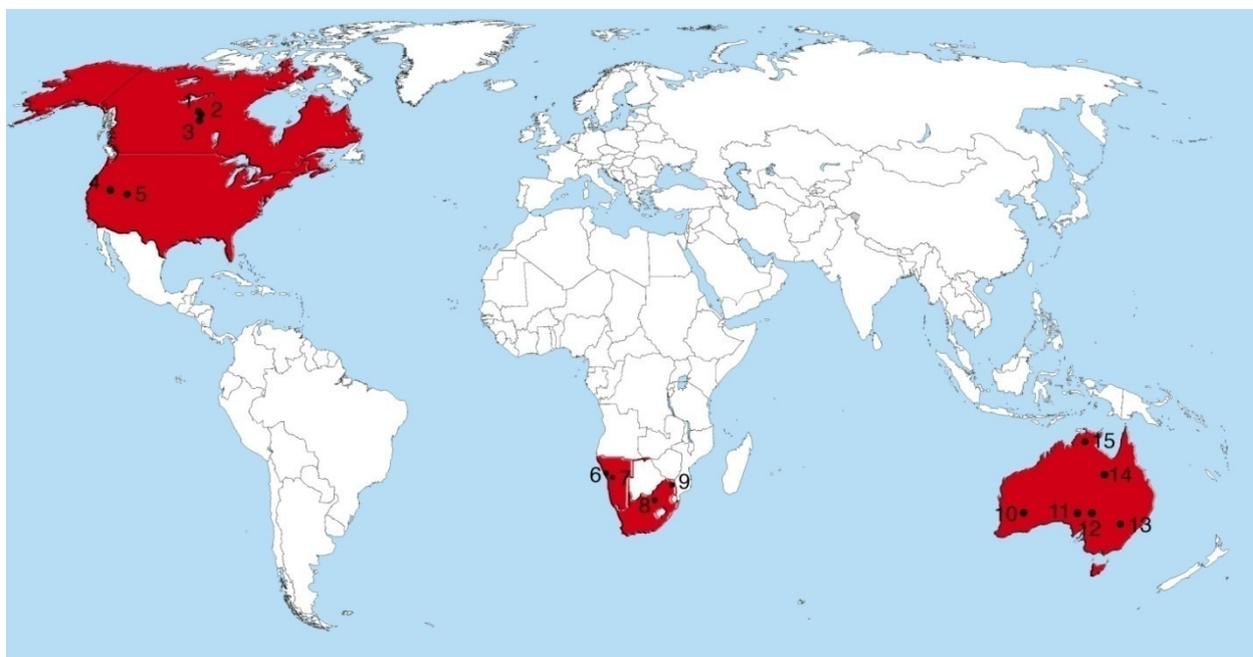


Fig. 3: The world map indicating the location of the specific mining operations of this study. 1: McClean Lake, 2: Rabbit Lake, 3: McArthur River/Key Lake, 4: Goldstrike, 5: Rössing, 6: Kennecott Utah Copper, 7: Navachab, 8: Vaal River, 9: Palabora, 10: KCGM, 12: Olympic Dam, 13: Beverley, 14: Northparkes, 15: Mount Isa, 16: Ranger.

Mineral	Mine	Company	Country	Method
Uranium	Beverley Mine	Heathgate	Australia	ISL
	McArthur River/Key Lake	Cameco	Canada	Underground
	McClean Lake	Areva	Canada	Open pit
	Olympic Dam	BHP Billiton	Australia	Underground
	Rabbit Lake	Cameco	Canada	Underground
	Ranger Mine	Rio Tinto - ERA	Australia	Open pit
	Rössing Mine	Rio Tinto	Namibia	Open pit
Gold	Goldstrike property	Barrick	USA	Open pit and Underground
	Kalgoorlie Consolidated Gold Mines	Newmont Australia Limited, Barrick Gold Corporation	Australia	Open pit and Underground
	Navachab	AngloGold Ashanti	Namibia	Open pit
	Vaal River	AngloGold Ashanti/Rio Tinto	South Africa	Underground
Copper	Kennecott Utah Copper	Rio Tinto	USA	Open pit
	Mount Isa Mine	Xstrata	Australia	Underground
	Northparkes	Rio Tinto	Australia	Open pit and Underground
	Palabora	Rio Tinto	South Africa	Open pit

Tab. 2: Table summarising the investigated operations.

7.1 Uranium Mines

The selected mines are all among the top twelve of the most productive uranium mines in the world (WNA: World Uranium Mining 2008).

7.1.1 The Beverley Mine

The Beverley uranium mine in South Australia was discovered in 1969 (Mindat.org: Beverly Mine...Australia 2008) and production began in 2001 (Heathgate Resources: Timing 2005). The mine uses the in situ leaching (ISL) method to extract the uranium, which is contained in three zones at depths of about 110 and 140 metres. It is expected that lifetime of the mine is 15-30 years (Heathgate Resources: The Mine 2005). The ore was originally planned to be mined with open pit operations (Heathgate Resources: Heathgate Resources 2005).

The Beverley Mine is entirely owned by Heathgate Resources Pty. Ltd. According to Heathgate, the Beverley Mine is the most advanced ISL-mine in the world (Heathgate Resources: Sustainability 2006).

634 tonnes of uranium was produced from the mine in 2007. Looking at world production statistics, there are two other ISL uranium mines, located in Kazakhstan and Uzbekistan, with higher annual production (WNA: World Uranium Mining 2008).

The ore is leached from the aquifer, where it is located, with oxygen and a weak acid, which is pumped through the ore body (Heathgate Resources: Uranium and the Beverly Deposit 2005).

7.1.2 McArthur River and Key Lake

McArthur River is the world's largest high-grade uranium deposit (Infomine: McArthur River 2006) and with a contribution of approximately 17% (7199 tonnes of uranium in 2007) of the total global uranium mining production it is the world's most productive uranium mine (WNA: World Uranium Mining 2008). It is located in northern Saskatchewan in Canada (Infomine: McArthur River 2006). The property is owned to about 70% by Cameco Corporation and to 30% by Areva (Cameco: McArthur River – Summary 2008).

The resources were discovered in 1988 and mining began in 1999. The ore, which occurs in deposits at a depth of between 500 and 600m (Infomine: McArthur River 2006) has an average ore grade of 20.7% U_3O_8 (Cameco: McArthur River – Summary 2008) and is broken by non-entry underground mining methods using remote controlled equipment in order to minimize employees' exposure to radiation. In some areas, the ore grade exceeds 40% U_3O_8 . Freezing techniques are used for groundwater control (Infomine: McArthur River 2006).

The broken ore is comminuted and processed into slurry in an underground processing circuit. The slurry is subsequently pumped to the surface where it is thickened and transported 80km by truck in specially designed shipping containers to Key Lake mill and processing plant (Infomine: McArthur River 2006). McArthur River is blended down to a feed grade of about 4% U_3O_8 , primarily for radiation protection purposes, with remnant ore which has been stockpiled from the mined-out pits at Key Lake³. The mined-out pits are today being used as tailings facilities. Key Lake is the largest uranium mill in the world (Infomine: McArthur River 2006).

³ Brent Berg, Manager, Environmental Leadership, Cameco Corporation, personal communication (e-mail) 2008-09-10

The climate of the region is cold, sunny and dry, best described as sub-arctic, with temperatures ranging from +30°C in summer to -30°C in winter (Infomine: McArthur River 2006).

Both McArthur River mine and Key Lake mill are certified according to ISO 14001 since 2003 (Cameco: McArthur River – History 2007).

7.1.3 McClean Lake

McClean Lake is an open pit uranium mine located in northern Saskatchewan, Canada. The resources were discovered in 1979 and production began in 1999 (Infomine: McClean Lake 2006).

Areva Resources Canada Inc. owns the McClean Lake mine to 70%. 22.5% is owned by Denison Mines Inc. and the rest is owned by OURD Canada Co. Ltd (Areva: McClean Lake – quality and productivity 2008).

The property includes several deposits at a depth rarely exceeding 175 metres. Two of them have been mined out and one is now used as a tailings management facility (Infomine: McClean Lake 2006).

The production in 2007 amounted to 734 tonnes of uranium (WNA: World Uranium Mining 2008) and the grade of the reserves, including stockpiles, is 1.7% U₃O₈ (Areva: McClean Lake – quality and productivity 2008).

In 2000, McClean Lake was certified according to ISO 14001 as the first uranium mine with this certification in North America (Areva: McClean Lake – quality and productivity 2008).

7.1.4 Olympic Dam

Olympic dam is a multi mineral underground mine in South Australia owned by the global mining company BHP Billiton. The deposit was discovered in 1975 and extraction began in 1988 (Infomine: Olympic Dam 2007). It is the world's largest uranium deposit, the world's fourth largest copper deposit, the fifth largest gold deposit and it also contains significant amounts of silver (BHP Billiton: Olympic Dam 2008). Olympic dam, with an annual output in 2007 of 3388 tonnes of uranium, accounts for 8% of total global uranium production, which makes it the world's third largest uranium producer (WNA: World Uranium Mining 2008). A further expansion plan of the mine, which would double its production capacity, is currently being planned and is to be presented to environmental authorities (BHP Billiton: About Olympic Dam 2008).

The operations are carried out in Australia's largest underground mine (Infomine: Olympic Dam 2007). If expansion plans are completed, it would make Olympic Dam the largest mine in the world and operations will eventually be converted from current underground mining, to an open pit (Mining-technology.com: Olympic Dam Copper-Uranium Mine 2008).

The ore, which mainly consists of sulphide minerals and pitchblende, has a copper grade of 2.1%, 0.7kg/t U₃O₈, 0.8g/t gold and 4.5g/t silver (Infomine: Olympic Dam 2007).

The copper ore is recovered by copper sulphide flotation from slurry before the concentrate is smelted and electrorefined to high purity copper. The uranium is recovered after flotation, together with remaining copper, by leaching with sulphuric acid. The copper and uranium streams are subsequently separated with solvent extraction methods (Infomine: Olympic Dam 2007).

The mine is located in an arid environment with no reliable sources of surface water, so water is piped from artesian wells and daily consumption exceeds 30 million litres. Average daily temperature range is 20-36°C in January and, 18-24°C in July (Infomine: Olympic Dam 2007).

In 2005, Olympic Dam received a partial environmental certification according to ISO 14001 criteria, while the operations showed some non-conformances (Infomine: Olympic Dam 2007).

7.1.5 Rabbit Lake

The ore body in Rabbit Lake, located in Saskatchewan in Canada, was discovered in 1968 and production began in 1975 (Cameco: Rabbit Lake – History 2008). The property consists of one mined out open pit, today used as a tailings management facility, and several mined out underground ore bodies as well as one active underground mine (Cameco: Rabbit Lake – Mining and Milling 2008). Production in 2007 was 1544 tonnes of uranium (WNA: World Uranium Mining 2008). Ore reserves have an average grade of 1.14% U₃O₈ (Cameco: Rabbit Lake – Reserves 2007).

Rabbit Lake is entirely owned and operated by Cameco (Cameco: Rabbit Lake – Summary 2008).

7.1.6 Ranger Mine

The Ranger open pit uranium mine, located in Australia's Northern Territory, is the world's second largest uranium producer accounting for 11%, and 4589 tonnes of uranium, of total world production (Infomine: Ranger 2006 & WNA: World Uranium Mining 2008). Ranger mine is owned and operated by Energy Resources of Australia Ltd (ERA), which is owned by Rio Tinto to 68.4% (Infomine: Ranger 2006). The ore bodies were discovered in 1969 and production began in 1981 (ERA: History – Ranger 2006).

The operations are located in the Kakadu National Park World Heritage area, which is subject to monsoonal rainfall resulting in tropical vegetation. Water management is an important issue due to the sensitive environments and the large amounts of water received (Infomine: Ranger 2006).

The operations include, apart from mills, crushers and uranium process plants, an electric power plant and a sulphuric acid plant (Infomine: Ranger 2006), which was decommissioned in January 2008 (ERA: Acid Plant 2006). The Ranger power plant supplies power to the mine and the nearby town of Jabiru, which was originally built by ERA to house workers at the mine.

ERA achieved environmental certification under ISO 14001 in 2003 (ERA: Environmental Certification 2006).

7.1.7 Rössing

The Rössing Mine is an open pit uranium mine situated in the Namib Desert of Namibia, Africa. The low grade ore deposit at Rössing is the largest of its kind and the overall grade is 0.034% U₃O₈. The mine was discovered in 1928 but production did not begin until 1976 (Infomine: Rössing 2007). With a production of 2583 tonnes of uranium in 2007, representing 6% of global uranium production it is the fifth largest uranium mine in the world (WNA: World Uranium Mining 2008). The life of the mine has been extended from planned closure in 2009 to continue until 2021 (Rio Tinto: Rössing's business at a glance 2008).

The largest owner of the mine is Rio Tinto with a share of 69%. The rest is owned by the government of Iran, 15%, the Industrial Development Corporation (IDC) of South Africa, 10%, the Namibian Government, 3%, and local individual shareholders own the remaining 3%. However, the Namibian

Government has the majority, 51%, of the voting rights (Rio Tinto: Rössing's business at a glance 2008).

Haul trucks in the mine drive on trolley-assist on the ramps (Infomine: Rössing 2007). Trolley assist is a system in which AC-current is supplied to the trucks, which are equipped with a pantograph, by overhead power lines, which potentially can reduce diesel consumption (Ford 2006).

The region of the Namib Desert is very hot during the summer period between November and February with temperatures exceeding 40°C. Daytime temperatures during the coldest months are usually above 20°C but with potentially sub-zero temperatures at night. Rainfall and water is scarce and Rössing uses 27% of total water used in the central Namib area (Infomine: Rössing 2007).

ISO 14001 environmental certification was received in 2001 and it was renewed in 2005 (Infomine: Rössing 2007).

7.2 Copper mines

The following investigated copper mines are among the worlds largest, located within regions close to the uranium mines selected.

7.2.1 Kennecott Utah Copper

The open pit in Kennecott Utah Copper, also known as the Bingham Canyon Mine, has been operated since 1904. It is the worlds largest copper mine (Rio Tinto: Kennecott Utah Copper 2008). It is the third largest gold producer in the United States and it also extracts significant amounts of silver and molybdenum as bi-products.

The operations are located approximately 20 miles southwest of Salt Lake City in Utah, USA. The temperature in the area is -7 to 2°C in January and ranges between 16 and 34 in July (Infomine: Bingham Canyon 2006).

The orebody in Bingham Canyon is a sulphide mineralization (Infomine: Bingham Canyon 2006). The ore is mined from the 4 km long and 1,2 km deep pit, known as the largest man made excavation on earth (Rio Tinto: Kennecott Utah Copper 2008)

Kennecott is certified according to ISO 14001 Environmental Management System (Kennecott Utah Copper 2008).

7.2.2 Mount Isa Copper Mine

The Mount Isa mine is one of the largest underground mine complexes in the world and includes two separate operations, that is copper recovery and zinc-lead process streams (Xstrata: Mount Isa Mine Sustainability Report 2007 2008). The area, Mount Isa in Queensland, Australia, is situated 2200km northwest of Brisbane. A large area of Queensland is in the tropics and it is usually hot and sunny in the state (Infomine: Mount Isa 2006).

The copper operations at Mount Isa consist of the two underground mines, a concentrator and a smelter (Infomine: Mount Isa 2006). The Mount Isa operation started in the mid 1920s, when zinc and lead were mined. Except brief operations during the Second World War, it was not until 1953 that copper was produced in parallel with the zinc-lead (Xstrata: Mount Isa Mine 2008). The ore in Mount Isa is expected to cover operations for at least eleven more years, counting from late 2006 (Mining-technology.com: Mount Isa Copper Mine 2008).

Sulphide minerals make up the copper ore body at Mount Isa. The ore, with a copper mineral grade of 3.4% (Xstrata: Production Data – Xstrata Alloys 2008) is mined in the two underground mines, crushed, hauled to the surface and separated from waste material through copper concentration. From the smelter, copper anodes containing 99.7% pure copper are transported to Xstrata Townsville Copper refinery for further refinement to copper cathodes (Xstrata: Mount Isa Mine Sustainability Report 2007 2008).

The mill is certified according to the environmental management system ISO 14001 (Xstrata: Mount Isa Mine Sustainability Report 2007 2008).

7.2.3 Northparkes

Northparkes Mines, producing copper and gold, is a joint venture between Rio Tinto (80%) and the Sumitomo Group (20%). It is located at Goonumbla, 27 km north/northwest of the town of Parkes in Central West NSW, Australia. The temperature in the region is normally hot in summertime to regular frosts in the winter and the average rainfall is of 588mm per year (Infomine: Northparkes 2006).

The approval for mining at the site was granted 1992, even though the ground had been explored since the early 1970's. The copper and gold are predominately contained in sulphide mineral. The copper content is 0.5% to 1.5%, while gold occurs in a grade ranging between 0.3 to 1 grams per tonne ore (Infomine: Northparkes 2006).

Northparkes consists of two open pits and one underground mine. The mined ore is crushed, milled and concentrated in on-site facilities. The resulting concentrate contains copper but also gold and silver which increases the value of the product (Rio Tinto: Northparkes Mines Sustainability Report 2007 2008).

Northparkes owns 6000 hectares of land around the mine. Only 1 630 of these are covered by the mining lease. The rest is farmed using best practice conservation farming by either a manager employed by the company or leased to local landowners (Rio Tinto: Northparkes Mines Sustainability Report 2007 2008).

The Northparkes Mines' Environmental, Safety and Health Management System (ESHMS) is certified according to ISO 14001 (Rio Tinto: Northparkes Mines Sustainability Report 2007 2008).

7.2.4 Palabora

Palabora is situated 360 km northeast of Pretoria, in the Northern Province of South Africa (Infomine: Palabora 2005). The largest shareholders of the company are Rio Tinto (57.7%) and Anglo-America (28.9%) (Mining-technology.com: Palabora Copper Mine 2008). Palabora is the leading copper producer in the country but it also mines valuable bi-products such as zirconium chemicals, uranium oxide, magnetite, nickel sulphate and small quantities of gold, silver and platinum. The copper ore grade is 0.7% (Infomine: Palabora 2005).

Palabora was an open pit copper mine from 1964 to 2002, when it became an underground mine. Palabora produces about 80 000 tonnes refined copper per year. Beside copper cathodes for export, the refinery produces cast rod for the domestic market (Infomine: Palabora 2005).

The mine is located near Kruger National Park, South Africa's biggest eco-tourism attraction. The Palabora operations are therefore closely monitored by different shareholders, e.g. the government

and environmental groups. The climate in the region is in general sunny and mild all year around with summer temperatures ranging between 15 and 30°C (Infomine: Palabora 2005).

The Palabora is an underground mine. The recovery process is made up of concentrator, a copper smelter and refinery. Copper anodes from the smelter, with a purity of 99.5%, are treated with electrolysis to form 99.99% pure copper cathodes. From the electrolytic refining, precious metals are removed from the copper, which can be retained and sold to refineries (Infomine: Palabora 2005).

Palabora was one of the first mining companies in South Africa that implemented ISO 14001 environmental management system, which they did as early as 1998 (Infomine: Palabora 2005).

7.3 Gold Mines

As in the case of the copper mines, a number of gold mines, in regions near the uranium mines, have been selected for the comparative study.

7.3.1 Goldstrike

The Goldstrike property consists of an open pit and two underground gold mines located in Nevada, USA. The site is owned by Barrick Gold Corporation and the property was first mined in 1976. The climate of the area, which is located at an altitude of 1700 metres, is relatively dry all year round with warm summers and cold winter (Infomine: Goldstrike 2006).

The gold, which is found in sulphide ores at an average grade of 0.143oz/ton (4 ppm) is processed into doré at site and shipped to an outside refinery for processing into gold bullion (Infomine: Goldstrike 2006).

Production in 2007 amounted to 1.63 million ounces (Barrick: Global Operations - Goldstrike Property 2007), and approximately 1800 people work on site (Infomine: Goldstrike 2006).

Goldstrike has two processing facilities: a roaster to treat carbonaceous ore and one autoclave installation to treat non-carbonaceous sulphide ore (Infomine: Goldstrike 2006).

7.3.2 Kalgoorlie Super Pit – Fimiston Operations

The Kalgoorlie operations are situated about 600 km east of Perth in Western Australia, at the south-east corner of the city Kalgoorlie-Boulder (KCGM 2008). It is an equally shared joint venture between Barrick gold of Australia and Newmont Australia Ltd, and consists of the Fimiston open pit (more commonly called the Super Pit), Mt Charlotte underground mine, Fimiston Mill and the Gidji Roaster. On behalf of the owners, the Kalgoorlie operations are managed by the company Kalgoorlie Consolidated Gold mines, KCGM. KCGM produces approximately 600 000 ounces of gold every year, which makes it the largest gold producing company in Australia (KCGM 2008) and most of it is mined at the Super Pit (Infomine: Kalgoorlie 2006). The Super Pit will, when completed, be 3.5km long, 1.5 km wide and as much as 640 meters deep at some places (KCGM 2008). The Kalgoorlie area has been mined since 1893 and KCGM has proven reserves that are calculated to last until 2013 (Infomine: Kalgoorlie 2006).

Kalgoorlie is situated in the Western Australian desert. The climate in the area is dry, with an average and evenly distributed rainfall of 260 mm. The summers are hot and the winters are cool (Infomine: Kalgoorlie 2006).

The goldfield in Kalgoorlie is made up of several isolated deposits of sulphide ore, of which the Gold Mile is the largest deposit, accounting for about 90 percent of the gold production from the field. The mineral grade of the ore mined was 2007 2.01 g/t⁴.

Ore is treated at the Fimiston Mill. The resulting sulphide concentrate is transported 20 km to the Gidji roaster where, after treatment, the golden-laden carbon is shipped once again back to the mill for processing. Finally, doré is shipped for refinement into gold bullion in Perth (Infomine: Kalgoorlie 2006).

There are no records of an implemented management system. However, according to the report Barrick Responsibility – 2007 Environmental, Health, Safety and Social Performance (2008), the company is working with the implementation of an environmental management system at all their operations.

7.3.3 Navachab

Navachab is situated on the southwest coast of Namibia, 10 km southwest of Karibib and 170 km northwest of Windhoek. The operation is fully owned by AngloGold Ashanti and has been in production since 1989. The Navachab gold deposit consists of greenschist-amphibolite facies, calc-silicate, marbles and volcano-clastics. The gold grains are very fine and associated with pyrrhotite and some traces of pyrite, chalcopyrite, maldonite and bismuthinite (AngloGold Ashanti: Country Report Namibia 07 2008).

The Navachab operation includes an open pit mine and its processing plant. The processing plants consist of mills, carbon-in-pulp and electro-winning facilities (AngloGold Ashanti: Country Report Namibia 07 2008).

All of AngloGold Ashanti's operations have ISO 14001-based Environmental Management System in place, with external auditing and certification (AngloGold Ashanti: Country Report Namibia 07 2008).

7.3.4 Vaal River

The Vaal River operations are fully owned by AngloGold Ashanti and include the four underground mines: Great Nologwa, Kopanang, Tao Lekoa and Moab Khotsong. The operations are located near the towns of Klerksdorp and Orkney on the border of the North West and Free State province and the gold occurs in three different reefs, namely Vaal Reef, the Ventersdorp Contact Reef (VCR) and the Crystalkop Reef. The Vaal River complex also includes four gold plants, one uranium plant and one sulphuric acid plant. The uranium diuranate, or yellow cake, produced at the operations is a bi-product to the gold production⁵. All together the operations produced 35.3 tonnes of gold in 2007 and the ore grade ranges between 3.62 and 7.94 g/tonnes (ppm) (AngloGold Ashanti: Country Report South Africa Vaal River Operations 07 2008).

⁴ Louise Crogan, Community Relations, Kalgoorlie Consolidated Gold Mines, personal communication (e-mail) 2008-08-08

⁵ Tony Da Cruz, Environmental Manager, AngloGold Ashanti Ltd, personal contact (e-mail) 2008-07-17

8 Companies Operating the Mines

The following companies are responsible for the operation of the mines described in chapter seven.

8.1 AngloGold Ashanti

AngloGold Ashanti, with headquarters in Johannesburg, South Africa, has operations situated in South Africa, Australia, Ghana, Mali, Brazil, Tanzania, the United States, Guinea, Argentina and Namibia. The company produced 5.5 Moz gold in 2007 employed the same year approximately 62000 people, including contractors (AngloGold Ashanti: Country Report Namibia 07 2008).

8.2 Areva

Areva has manufacturing facilities in 43 countries and over 65000 employees (Areva: In brief 2008). It has operations in all steps of the nuclear energy life cycle from the mining of the uranium to treatment and recycling of used fuel, including reactor construction and electricity transmission (Areva: Operations 2008).

8.3 Barrick Gold Corporation

Barrick Gold Corporation is the leading gold mining company of the world with 27 operating mines and 10 development projects in five continents. The company was founded in 1983 (Barrick: History 2007).

8.4 BHP Billiton

BHP Billiton is the world's largest diversified resource company with 41000 employees working in 100 operations in 25 different countries. Commodity businesses included in the company's operations are aluminium, energy coal and metallurgical coal, copper, manganese, iron ore, uranium, nickel, silver and titanium minerals, and it has interests in oil, gas, liquefied natural gas and diamonds. Its global headquarters are located in Melbourne with major offices in London (BHP Billiton: Company Profile 2008).

8.5 Cameco Corporation

Cameco is the world's largest uranium producer accounting for 19% of global production. It has four operating mines located in Canada and in the USA. Furthermore, Cameco is one of three uranium conversion suppliers in the western world and it also owns or controls 35% of the western world's uraniumhexafluoride production capacity (Cameco: Company Profile – Overview 2007).

Cameco was formed in 1988 by the merger of Saskatchewan Mining Development Corporation and Eldorado Nuclear Limited (Cameco: Company Profile – History 2007). Cameco is also involved in the Gold mining industry by owning 53% of the shares in Canadian based gold mining and exploration company Centerra Gold (Cameco: Other Investments 2008).

8.6 Heathgate Resources Pty Ltd

Heathgate Resources, with its head office in Adelaide, South Australia, is an affiliate of General Atomics. It was formed in 1990 when the former owners offered the Beverley mine for sale (Heathgate Resources: Who is Heathgate 2006). A workforce of about 150 people works at the Beverley mine (Heathgate Resources 2008).

8.7 Kennecott Utah Copper

Kennecott Utah Copper Corporation is a subsidiary company to Rio Tinto that operates the mine, the smelter and the concentrator at Bingham Canyon. Kennecott Utah Copper became the sole operator of the property year 1936 (Rio Tinto: Kennecott Utah Copper 2008) and since 1959, it has been a fully integrated copper producer with all four production steps; mining, concentration, smelting and refining (Rio Tinto: Kennecott Mine in Utah History 2008).

8.8 Rio Tinto

Rio Tinto is one of the world's leading mining and exploration companies. Their products include aluminium, copper, diamonds, energy products, gold, industrial minerals and iron ore (Rio Tinto: Who we are 2008) Rio Tinto is a combination of the companies Rio Tinto plc from UK and Australian Rio Tinto Limited. The British branch was founded already in 1873 (Rio Tinto: Timeline 2008). Rio Tinto operations are found in all five continents (Rio Tinto: Our Operations 2008).

8.9 Xstrata Plc

Xstrata is a global mining group with headquarters in Zug, Switzerland, and operations and projects in 18 countries around the world. The company employs 56000 people, including contractors and had 2007 sales of 28542 million USD. Xstrata is active in several mineral markets, including e.g. copper, coal, ferrochrome and nickel (Xstrata: Mount Isa Mine Sustainability Report 2007 2008).

9 Methodology

The sources to the primary data presented and analysed in this report can be categorised in different types. Primarily, the majority of the data used originates from official and public information provided by the companies operating the mines. This data is available in the form of printed or digital copies published online of reports often titled “Sustainability Report” or “Environmental Report” or in the form of information presented directly on the corporate web pages. Secondly, data is collected from organisations, independent environmental consultant companies or databases of national environmental authorities. The databases used in this study are the National Pollutant Inventory (NPI) of the Department of the Environment, Water, Heritage and the Arts of the Australian Government, the National Pollutant Release Inventory (NPRI) of Environment Canada and the Toxics Release Inventory (TRI) Program of the US Environmental Protection Agency. Reports from the Supervising Scientist of the Australian government and the Athabasca Working Group Environmental Monitoring Program in Saskatoon, Saskatchewan, Canada have also provided primary data. Finally, primary data also originates from direct personal communication with representatives at the different sites.

The primary data collected was converted to metric units in order to facilitate for comparison. Subsequently, for multi mineral mines, data was allocated to the specific mineral of interest based on the relative contribution of total sales of the investigated operations. In all cases of multi mineral mines except for Olympic Dam operations, the investigated mineral is the major product contributing to the majority of total sales. Olympic Dam is treated as a uranium mine although copper production contributes to 75% of total sales and gold and silver contribute to five percent (AUA 2008). This type of allocation does not take into consideration any processes or emissions that are related to one specific mineral only.

After allocation to the mineral of interest, the data was calculated to be expressed per tonnes of ore mined, tonnes of mineral produced and per million US dollar worth of product. In some cases, a distinction is made between ore mined and total movement. The latter also includes waste rock which has to be removed in order to extract the ore. For the Beverley mine, ore is not mined in traditional terms since the mineral is extracted with in-situ leaching and hence data cannot be expressed per tonnes of ore mined. Raw data is presented in *Appendix I: Primary Raw Data*.

Market mineral prices averaged for year 2007 are used to calculate the total value of the production and to make necessary allocations. Average market prices of gold and silver were calculated using 2007 London gold and silver fixes from London Gold Bullion Association (LBMA: 2007 London Gold Fixings 2008 & LBMA: 2007 London Silver Fixings 2008). Copper prices set at the London Metal Exchange were found in Xstrata Annual Report 2007 (2008) and prices on molybdenum were approximated using data presented by Infomine (Dynamic Prices and Charts for Molybdenum 2008). Since uranium is not traded on a common market but rather on long-term contracts, a price that is likely to reflect the production during 2007 was estimated by Ali Etemad at Vattenfall Nuclear Fuel⁶. The mineral prices used in this study are presented in *Tab. 3*.

All prices have been converted to USD per tonne. The prices of copper concentrate and copper anode have been derived based on the price of copper cathode, corrected for the copper content of the specific product and the relative operating cost of the specific process steps required to produce

⁶ Etemad, Ali, Vattenfall Nuclear Fuel, personal communication, 2008-11-07

the product compared to the total operating cost. Operating costs of the different process steps in copper cathode production are described in Davenport et al (2002).

Prices:	USD/tonne
Copper – concentrate	1 285
Copper – anode	6 393
Copper – cathode	7 139
Gold	22 374 055
Uranium - U ₃ O ₈	99 206

Tab. 3: Mineral prices used in this study.

9.1 Impact Category (parameter) Definition

The impact categories finally used for this study are based on a selection of parameters for which comparable data was available. It includes resources, human health and ecological consequences.

The data is presented in the following parameters for all sites:

- Energy usage
- Water usage
- Greenhouse gas emissions
- Emissions to air of sulphur dioxide, nitrogen dioxide and particulate matter
- Injury frequency rate

For operations located in Australia and the US, the extensive data available in the NPI and TRI databases respectively allow for an in depth analysis. The data from NPI and TRI have been classified into emissions to air, water and soil and characterised with Life Cycle Impact Assessment (LCIA) characterisation factors from Guinée (ed.) (2002). This was performed in order to reduce the number of parameters to simplify comparison. The characterisation resulted in the following additional parameters used in the analysis:

- Human toxicity potential
- Freshwater aquatic ecotoxicity potential
- Freshwater sediment ecotoxicity potential
- Terrestrial ecotoxicity potential
- Photo-oxidant formation potential
- Acidification potential
- Eutrophication potential

All emissions to water were treated as if the recipient is a freshwater ecosystem and all emissions to soil were treated as emissions to agricultural soil.

9.2 Characterisation

Characterisation is a quantitative way of translating environmental loads into a specified environmental impact using pre defined characterisation factors for all emissions. After characterisation, all emissions giving rise to a certain impact are expressed as one equivalent emission of a specified unit. With knowledge from scientific methods within environmental chemistry, toxicology, ecology etc, characterisation combines physicochemical properties of the pollutants and modelling of how pollutants react in the environment in order to assess the impact of

a pollutant in the environment. However, environmental systems are very complex and some characterisation methods are more developed than others (Baumann & Tillman 2004). Furthermore, sets of characterisation factors are not complete and some reported data might not be included in the model used.

Fig. 4 below illustrates schematically how characterisation can be used to translate emissions of various substances (environmental loads) into one environmental impact with the aid of characterization factors. This specific example shows how emissions of ammonia, nitrate, nitric acid and oxides of nitrogen result in eutrophication potential expressed in emissions of phosphate equivalents.

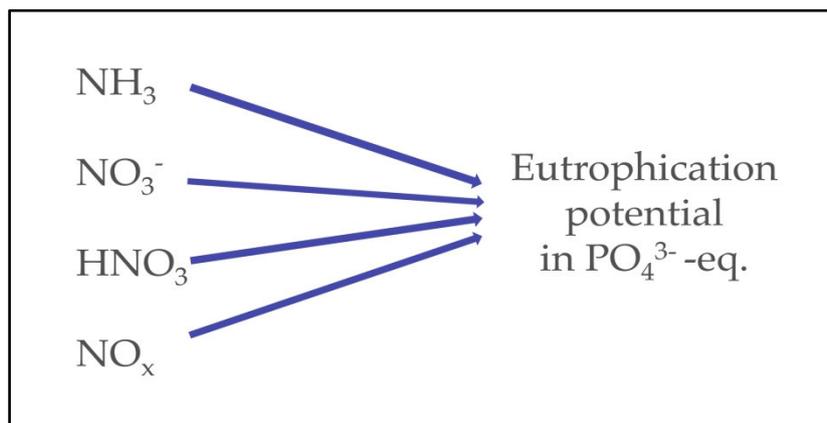


Fig. 4: Illustration of the principles of characterisation (adopted from Baumann & Tillman (2004).

As mentioned earlier, radiation and tailings are topics that are not included in any of the above mentioned parameters of this investigation. However, they are two very important aspects, which need to be investigated when studying the mining industry. Tailings are analysed using a simplified performance assessment methodology and radiation issues are analysed based on existing epidemiologic investigations, and dose rates to the public as well as occupational doses.

9.3 Environmental Loads for which Characterisation Methods are Lacking

Certain reported emissions of pollutants lack characterisation factors, which means that they are not included in the graphs presented in the results. Some of the most important environmental loads lacking characterisation factors are: cyanide, dioxins and what is grouped under total volatile organic carbons (VOC). Especially cyanide is a substance that possibly could have a large impact on the results since it is used in the extraction of gold. A complete list of characterisation factors used in this study can be found in *Appendix II: Characterisation Factors*. No emissions contributing to stratospheric ozone depletion have been reported.

9.4 Performance Assessment

The environmental impacts and health related issues from mine waste from the different mining operations have been analysed with a performance assessment methodology, inspired by the MiMi project and report issued 2004 (Höglund & Herbert eds. 2004). MiMi (Mitigation of the Environmental Impact from Mining Waste) is a multidisciplinary research project that was funded by The Swedish Foundation for Strategic Environmental Research (MISTRA) for the period 1997-2004. The project focused on the development of reliable prediction of the long-term function of deposit sites and the remediation of mining waste (Allard & Herbert eds. 2006). The performance assessment

methodology was originally developed by researchers in the radioactive waste management area. The aim of the performance assessment method is to systematically study all relevant processes and mechanisms influencing release rates from mining waste (Allard & Herbert eds. 2006).

In performance assessment, a number of conceptual and mathematical models are used to describe and quantify the main processes that govern the release and transport of different contaminants, as well as chemical and biochemical reactions from source to final recipient. For evaluations of long-term effects of different processes, studies of natural counterparts can be used as a support.

The analysis presented in this report does not include any calculations due to limited amounts of data available but the focus will instead be on general discussions. The enormous amounts of waste and tailings generated by the mining industry contain toxic materials that are connected to a number of environmental issues as well as health hazards. There is little specific data available within this field and the studies that have been performed do not cover a long enough period of time to allow for a long-term analysis. Since samples never or rarely exist from before the mining operations started, it is often extremely difficult to separate what is caused by mining operations from what is caused by geological and environmental conditions in the region.⁷

Consequently, in a very simplified form, the performance assessment methodology has been used to discuss a number of parameters that are of interest and consequences of changes within these parameters have been compared. Since the ore at Beverley Mine is extracted with in situ leaching, it is not included in the following analysis.

Six parameters were mentioned in chapter 5.3 as most relevant for tailings related issues and processes:

- The ore: source term and water chemistry
- Age of the operations
- Tailings management
- Metals and substances related to the different minerals and ores
- Process chemicals and complexes
- Geography: precipitation and hydrology

Since this study focuses on the current performance of different operations, the age of the operations and tailings will not be treated in the comparative discussion. The same goes for tailings management. Factors affecting the success of tailings management facilities are several and of interest but due to lack of data and inability to assess the performance of the different operations, this area will not be included.

The type of data required to perform a comparison is mostly unavailable. Therefore, the following comparison will only deal with some of the parameters of importance.

The parameters that are discussed are amounts of tailings generated, the type of ore, the metals usually connected to the specific type of ore, process chemicals and water conditions (mainly in the form of precipitation). All parameters are directly related to the specific operations, except contained metals and substances that instead are derived from the nature of the source term.

⁷Bert Allard, Professor in Chemistry, Örebro University, meeting at Örebro University November 3, 2008

10 Results and Analysis

This part will present the results from the different investigated parameters. When no result is displayed for a specific mine, the information is not available and it does not contribute to the average values displayed at the right hand side of the graphs.

10.1 Energy Use

Fig. 5 shows energy usage at each site expressed in GJ per million US dollar of product. Where such data is available, the energy usage is separated into direct energy and indirect energy. Direct energy refers to all energy consumed at site except electric energy. Indirect energy refers to electric energy consumed at site. For Beverley and Ranger mines, indirect energy constitutes the total primary energy in the natural gas required for on-site electricity production. Consequently, the electrical energy consumed is considerably lower than the indirect energy indicated on the graph.

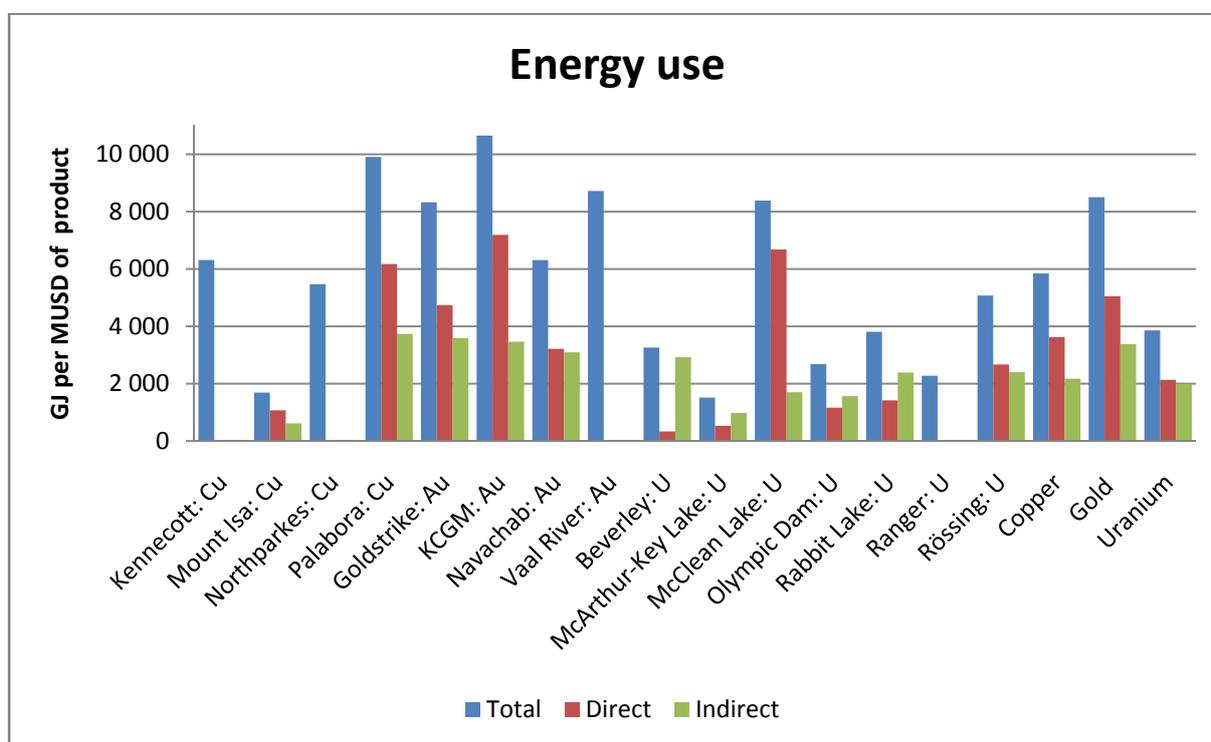


Fig. 5: Energy usage in GJ per MUSD of product.

The graph clearly shows that gold mines generally consume more energy per economic value of product produced. This could be explained by the very low grade of gold in the ore. This requires larger amounts of ore to be extracted in order to produce a given amount of mineral and consequently more energy is needed in the process. Uranium mines have the lowest average energy consumption per million US dollar of product.

10.2 Greenhouse Gas Emissions

Emissions of greenhouse gases from the investigated sites follow the same general trend as the energy usage and considering average greenhouse gas emissions per million US dollar of product, gold mines have the largest emissions and uranium mines the lowest emissions as can be observed in Fig. 6. When investigating relative individual trends however, there are some deviations from the reported total energy usage. This can result from differences in the way emissions from electricity

production are accounted for or due to different electricity production mixes. Although this study aimed to exclude variations from national or regional electricity production mixes, such a distinction was impossible to make due the fact that the sources of the emissions were not specified at all sites.

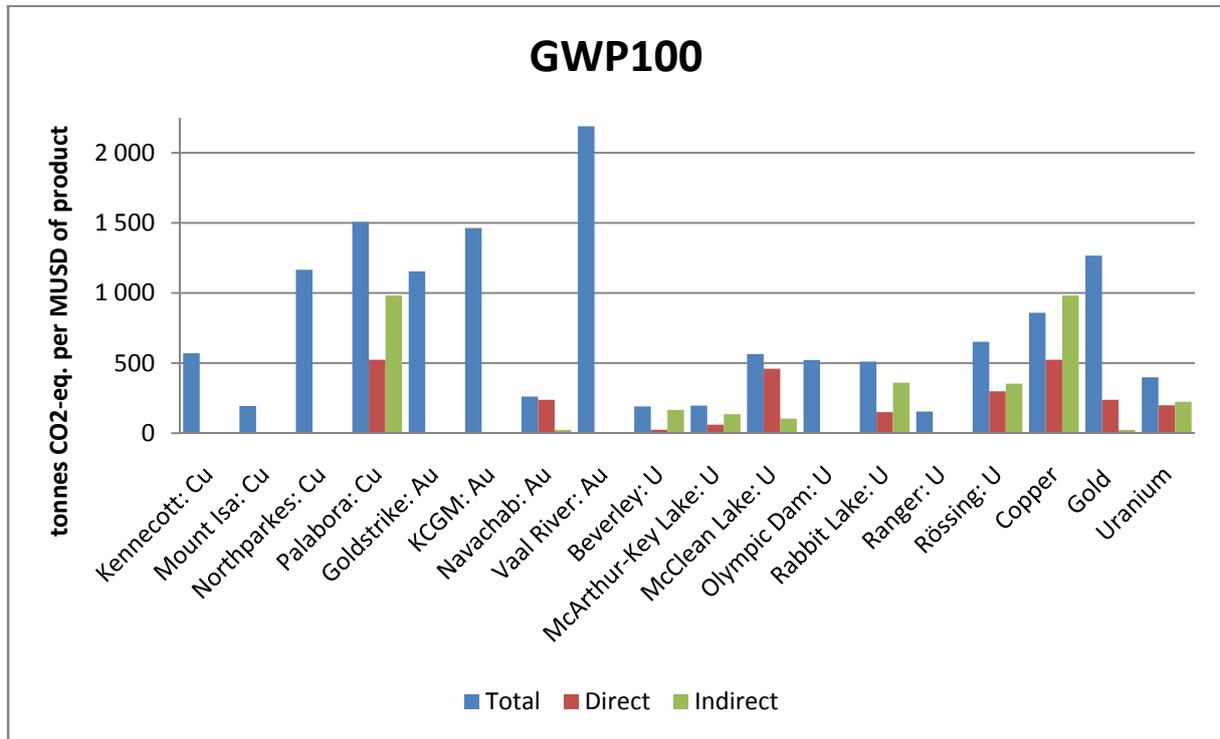


Fig. 6: Global warming potential in tonnes CO₂-equivalents per MUSD of product.

10.3 Water Usage

The average water usage, illustrated in Fig. 7, shows the same trend as for both energy usage and greenhouse gas emissions with gold mines having the highest and uranium mines having the lowest average water consumption per million US dollar of product. Water usage trends may be explained to a large extent by regional availability. Rabbit Lake uranium mine for example, located among several lakes in the north of Canada, have the highest consumption of water. However, this figure includes inflow to the mine or precipitation that has to be treated before it is released. While water may represent a problem due to its abundance in one site, it may be a problem due to its scarcity at other sites. It should be noted that the gold mines, having the largest water use, all operates in dry climates where water is a scarcity.

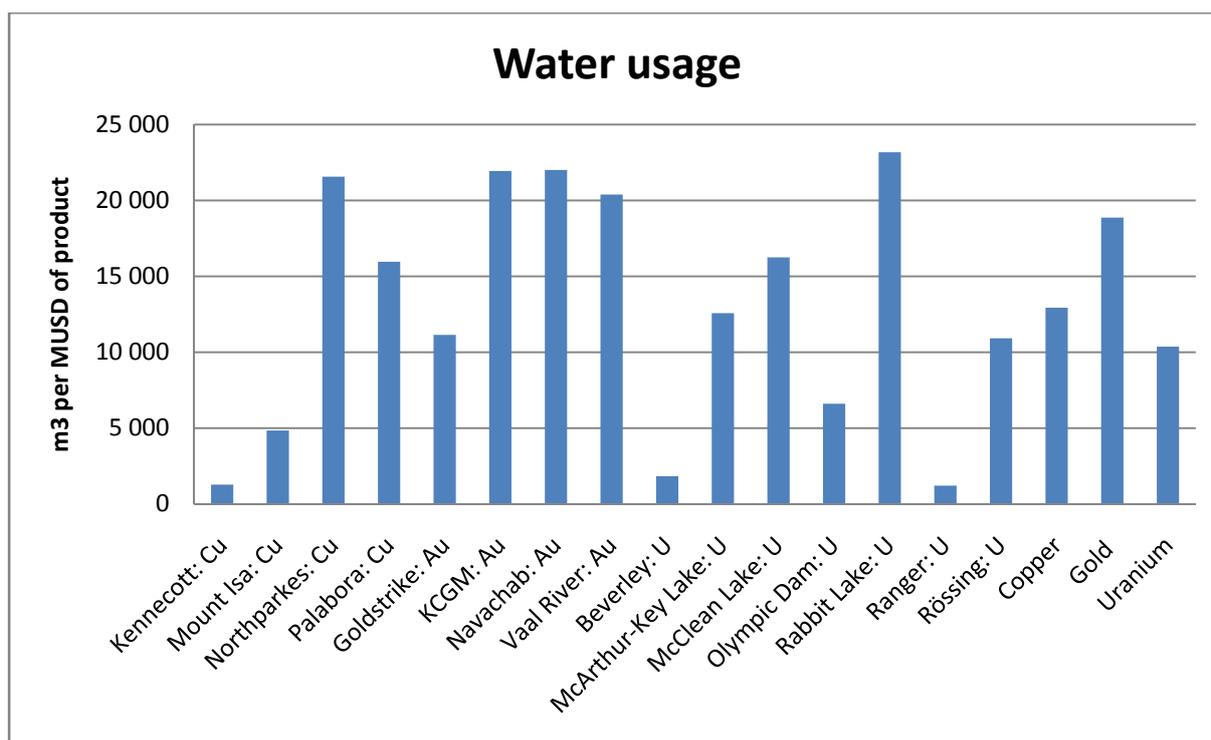


Fig. 7: Water usage in m^3 per MUSD of product.

10.4 Emissions to Air

Fig. 8 shows emissions to air of sulphur dioxide, nitrogen oxides and particulate matter. Some copper mines have emissions of sulphur dioxide that are several factors higher than for other mines. This is explained by the fact that the copper is contained in sulphide ores giving rise to large emissions of sulphur dioxide when the ore is roasted and smelted. The emissions of nitrogen oxides and particulate matter follow earlier trends connected to energy consumption and carbon dioxide emissions, i.e. gold have the highest emissions, followed by copper and last uranium mining. Combustion engines, power production and explosives are examples of sources to nitrogen oxides and particulate matter and are all closely connected to resource consumption that can be explained by a low ore grade. Hence, even if the data of nitrogen oxide emissions and particulate matter from gold mining is only available from KCGM and thus constitute the average value, these results appear reasonable.

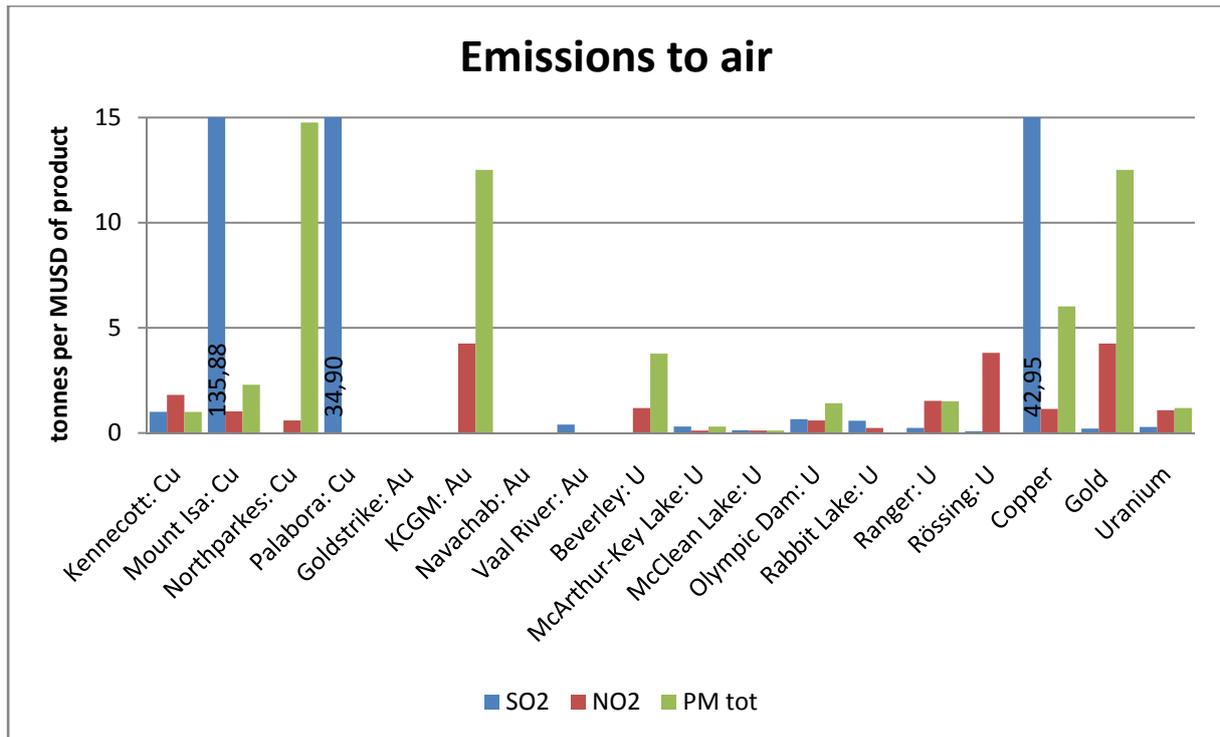


Fig. 8: Emissions to air of SO₂, NO₂ and Particulate Matter in tonnes per MUSD of product.

10.5 Injury Frequency Rate

In Fig. 9, the lost time injury frequency rate (LTIFR) per 200000 hours worked is displayed. The figures indicate each incident resulting in the employee requiring absence from work due to the incident. The figure does not take into account the severity of the incident nor the time required for recovery. For Vaal River, a fatal injury frequency rate (FIFR) is also displayed which shows the number of fatal injuries at work per 200000 hours worked. The uranium mines have the highest average LTIFR but considering also FIFR, gold mines could be valued higher.

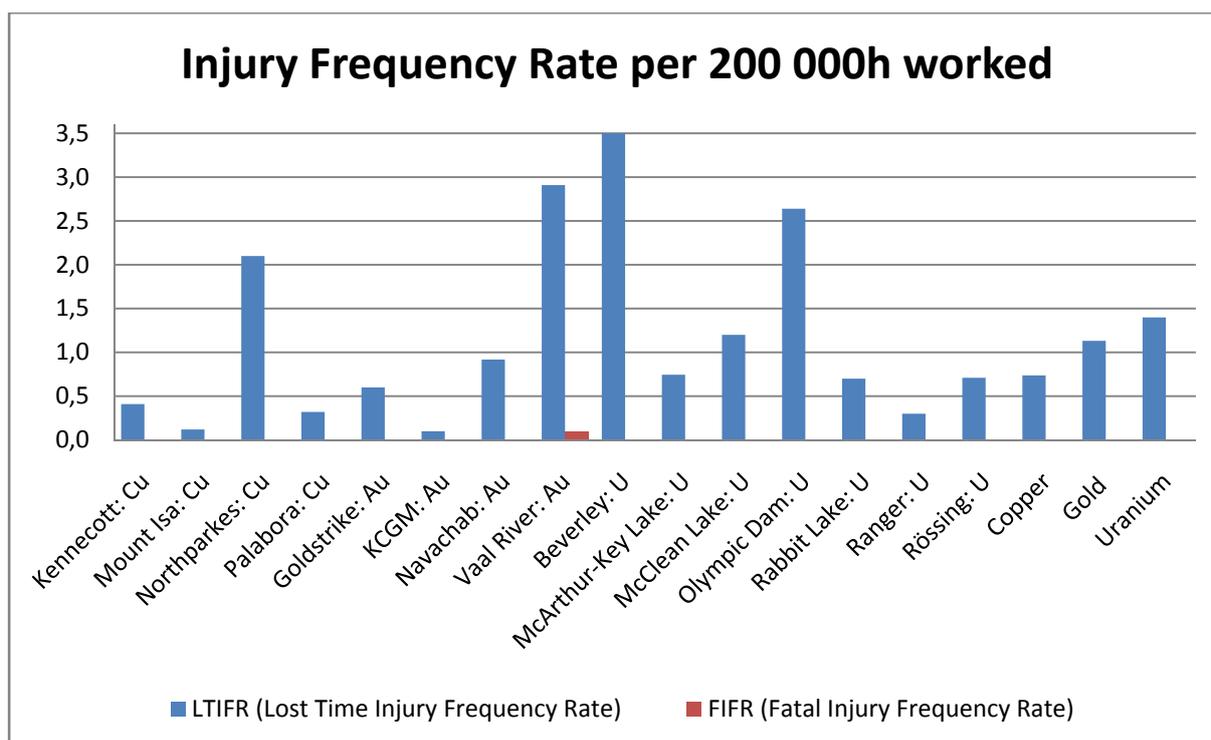


Fig. 9: Lost time, and fatal injury frequency rate per 200000h worked.

The highest value is surprisingly from Beverly mine, which is not a traditional mine but an in situ operation. As well, the range between the highest lost time injury frequency rates of different mines producing the same mineral is large for all minerals. The extent to which the LTIFR figures reflect the dangers of the work at the mine or is a subject to corporate policies or national legislation remains unknown.

10.6 Human Toxicity Potential

Human toxicity, as expressed in kg of 1,4-dichlorobenzene (DCB) equivalents in Fig. 10, shows very high levels for uranium mines. This is explained by the large emissions of polyaromatic hydrocarbons from the Olympic Dam operations. It should be noted that Olympic Dam is a multi mineral mine treated as a uranium mine in this study. 20% of the sales originate from uranium production and hence, 20% of the emissions are allocated to the uranium production. Gold mines show the lowest levels. The very low levels reported by the Goldstrike and Kennecott operations can be explained by varying reporting regulations between the NPI and TRI systems in Australia and the United States, as well.

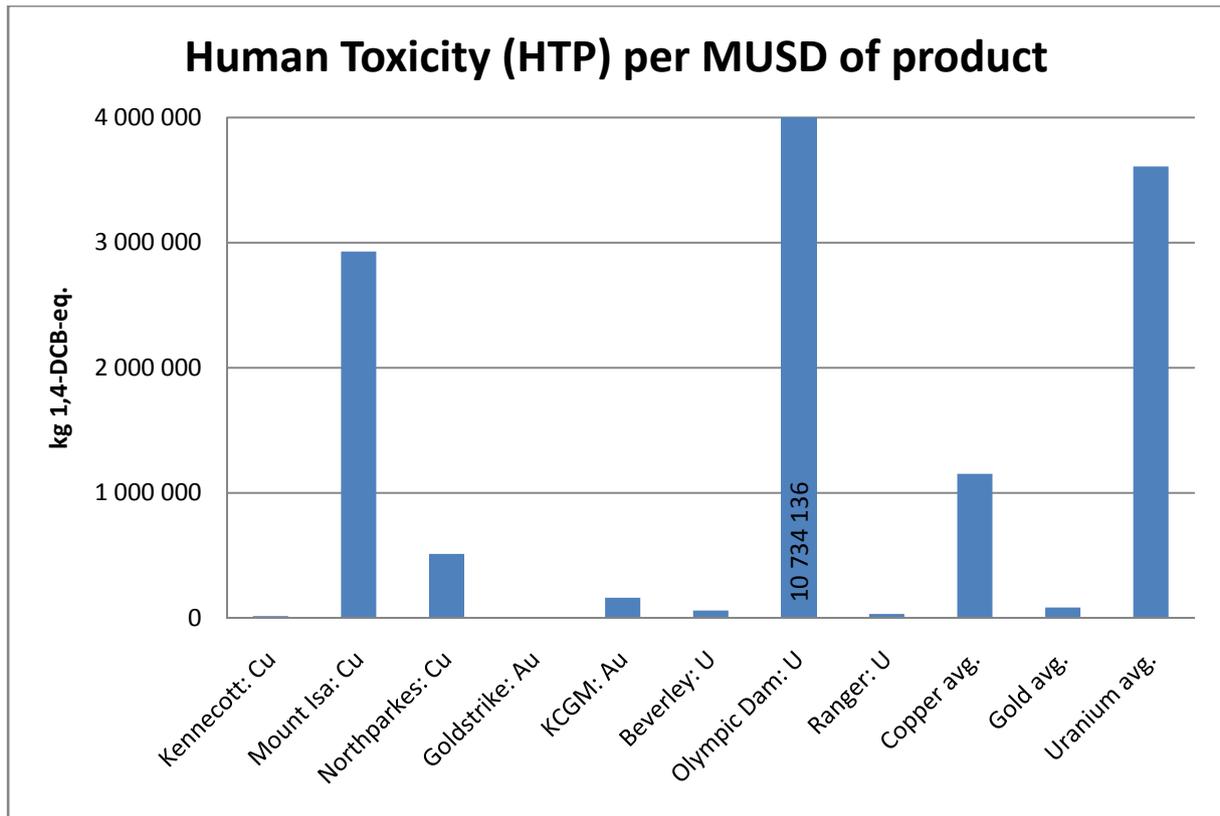


Fig. 10: Human toxicity potential in kg 1,4-dichlorobenzene per MUSD of product.

10.7 Ecotoxicity Potential

Impacts on ecotoxicity, expressed in kg of 1,4-dichlorobenzene (DCB) equivalents per million dollars of product show identical trends for freshwater aquatic ecotoxicity, freshwater sediment ecotoxicity and terrestrial ecotoxicity respectively. The copper mine average levels are very high mainly because of the elevated levels from the Mount Isa operations. The resulting high levels of ecotoxicity for Mount Isa and copper operations in general predominantly originates from emissions of heavy metals that in general are higher than for other operations. The results are shown in Fig. 11, Fig. 12 and Fig. 13.

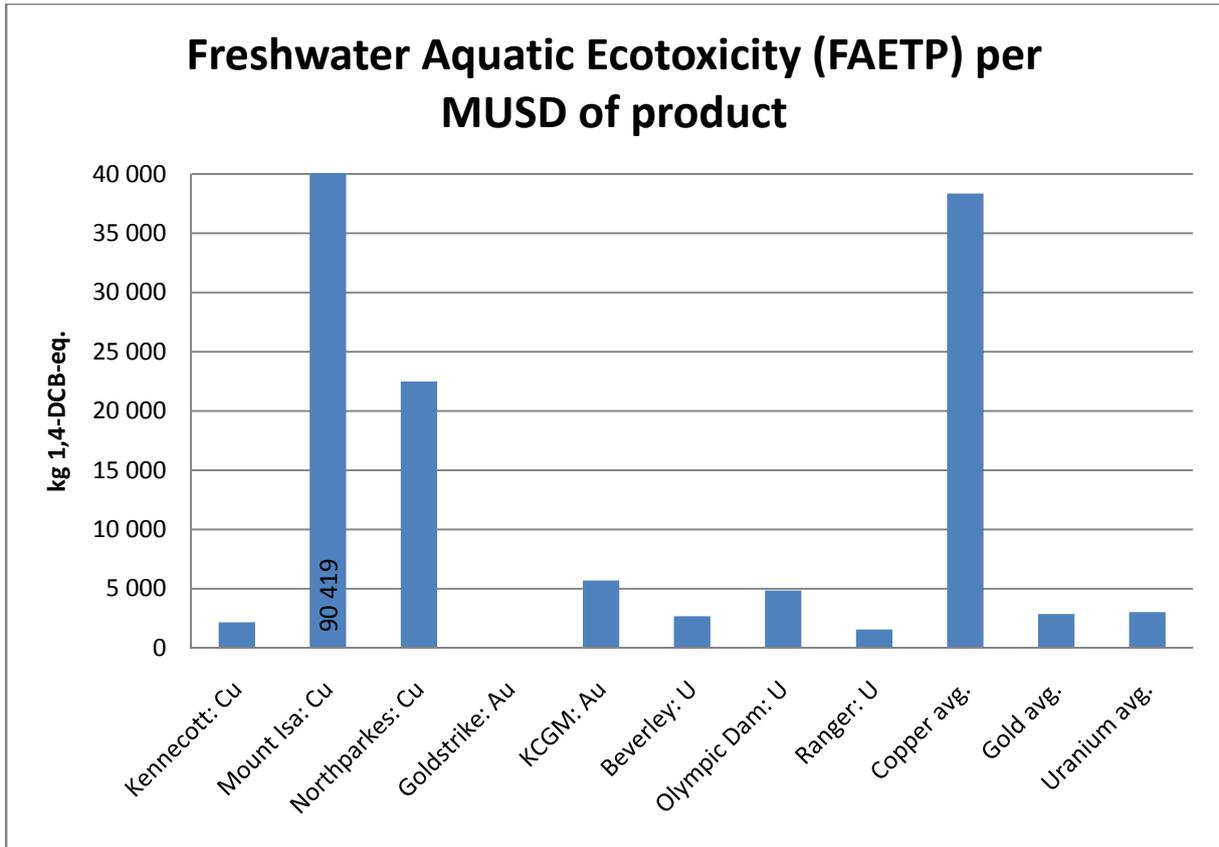


Fig. 11: Freshwater aquatic ecotoxicity potential kg 1,4-dichlorobenzene per MUSD of product.

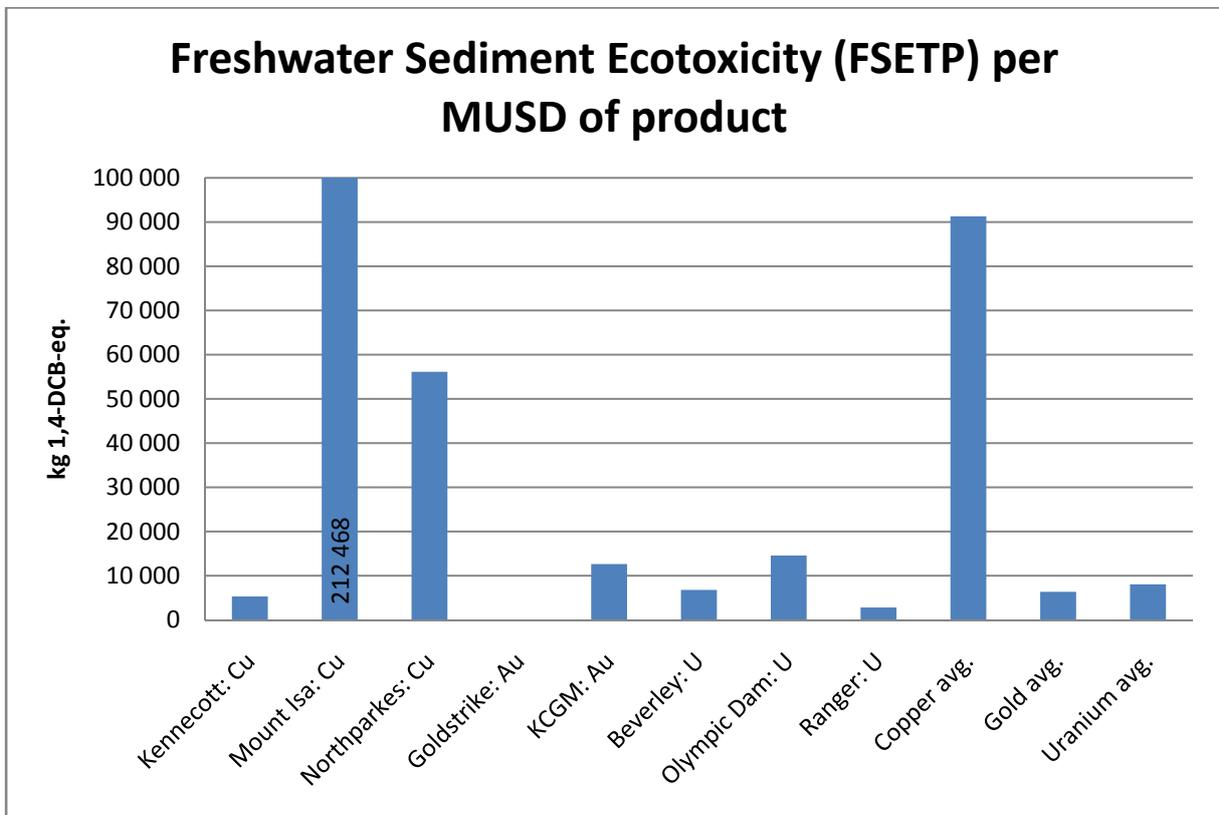


Fig. 12: Freshwater sediment ecotoxicity potential kg 1,4-dichlorobenzene per MUSD of product.

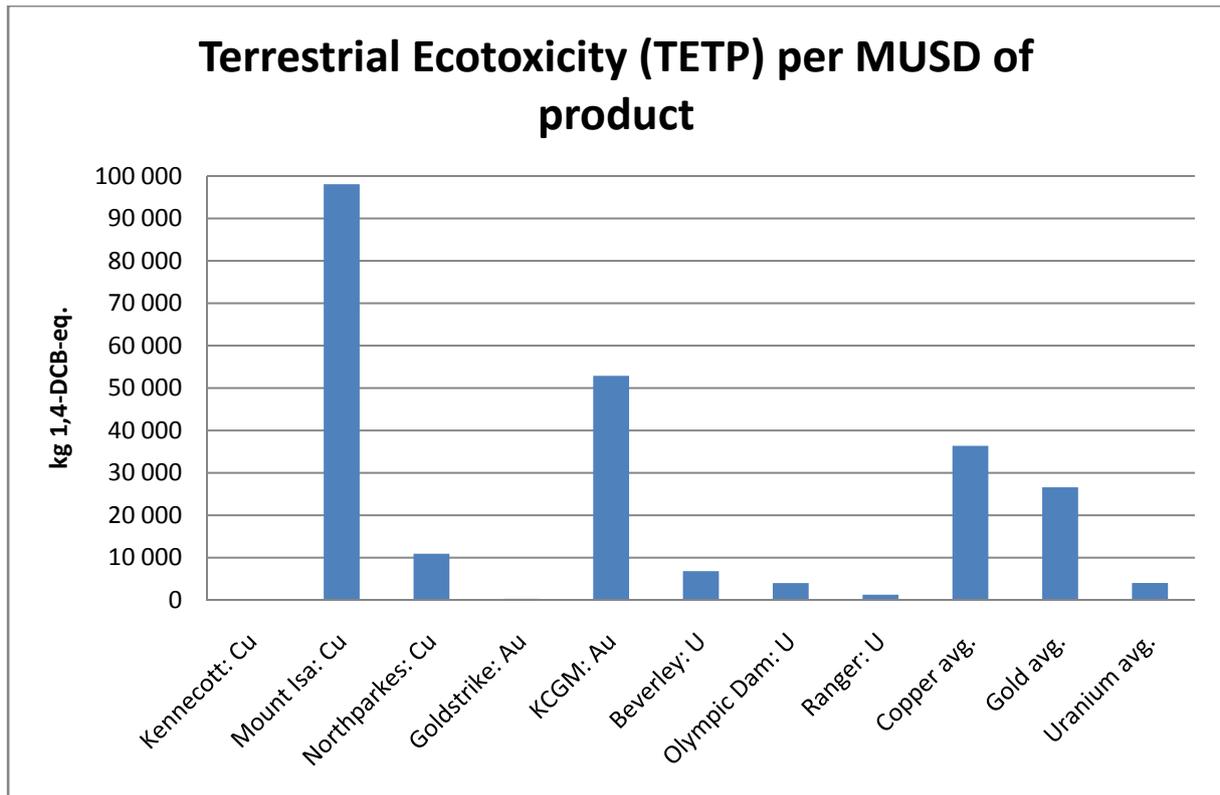


Fig. 13: Terrestrial ecotoxicity potential kg 1,4-dichlorobenzene per MUSD of product.

10.8 Photo-oxidant Formation Potential

Photo-oxidant formation levels, expressed in kg ethylene-equivalents in Fig. 14, again show very high levels for noticeably Mount Isa operations and copper operations in general. Gold and uranium mines show levels in the same order of magnitude. It should be noted that no emissions of oxides of nitrogen or oxides of sulphur are reported from Goldstrike operations. This influences the current average result for the gold mines positively.

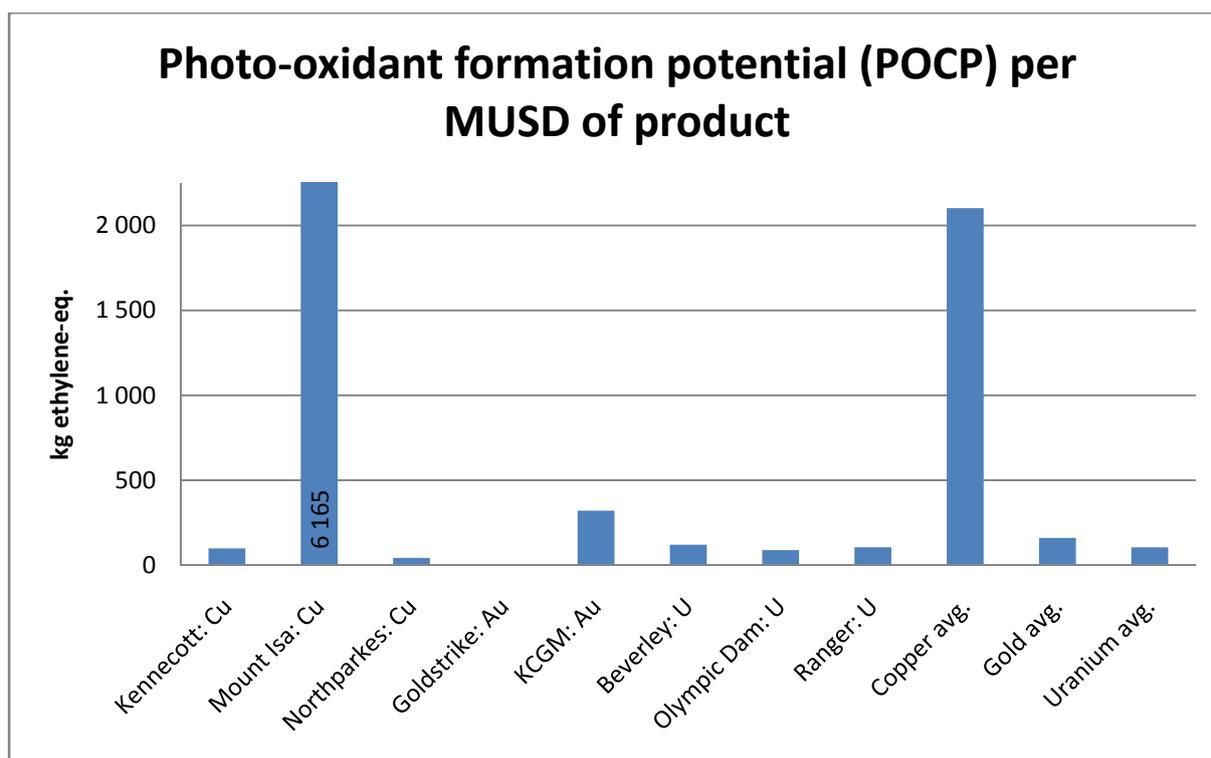


Fig. 14: Photo-oxidant formation potential in kg ethylene-equivalents per MUSD of product.

10.9 Acidification Potential

Acidification potential, which is illustrated in Fig. 15, is explained by emissions of sulphur dioxide that are very high from some copper operations. The average values are in the same order of magnitude for both gold mines and uranium mines although slightly lower for uranium operations. Once again, it should be noted that no emissions of oxides of nitrogen or oxides of sulphur are reported from Goldstrike operations. This influences the current average result for the gold mines positively.

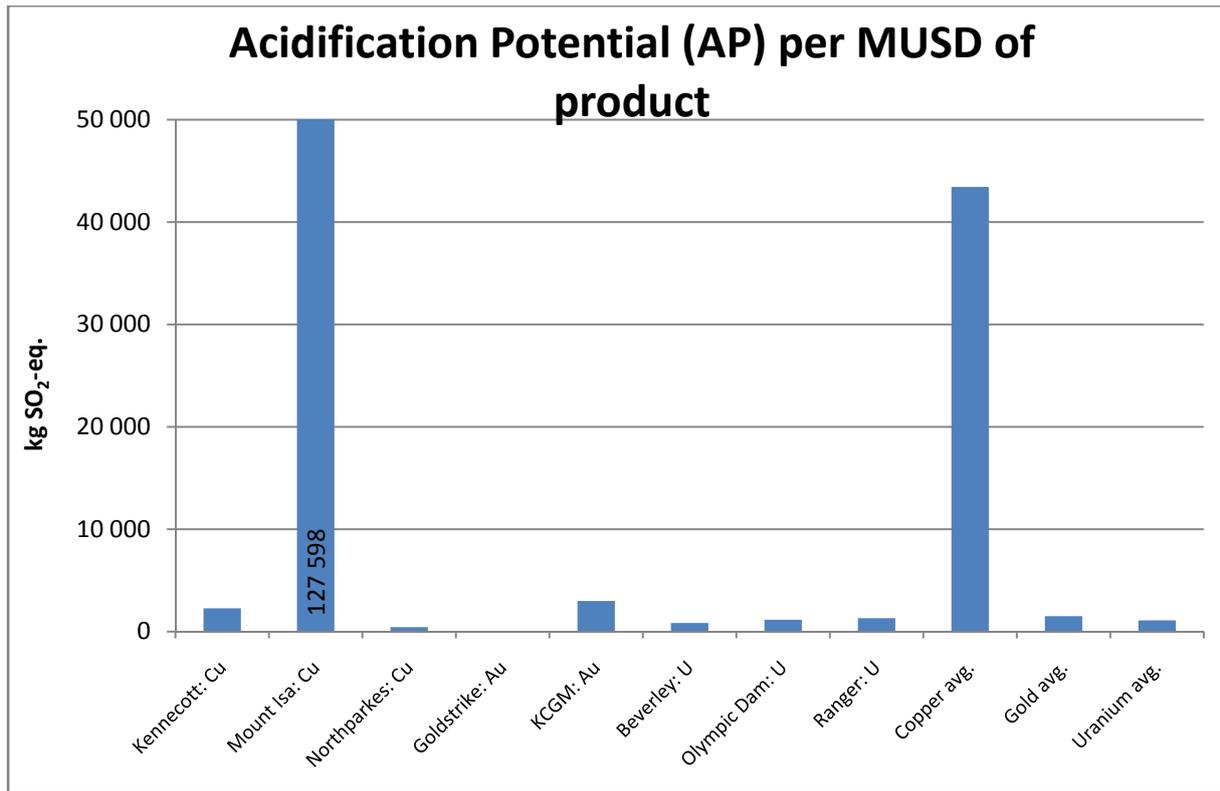


Fig. 15: Acidification potential in kg SO₂-equivalents per MUSD product.

10.10 Eutrophication Potential

While acidification potential is highly related to emissions of sulphur dioxide, eutrophication potential, shown in Fig. 16, is highly related to emissions of nitrogen oxides. This explains the very high levels shown by Kalgoorlie Consolidated Gold Mines (KCGM). Consequently, the average levels for gold mines are higher than for both copper and uranium mines which have levels on the same order of magnitude. If emissions of oxides of nitrogen were available from Goldstrike operations, it would influence the average result for the gold mines negatively.

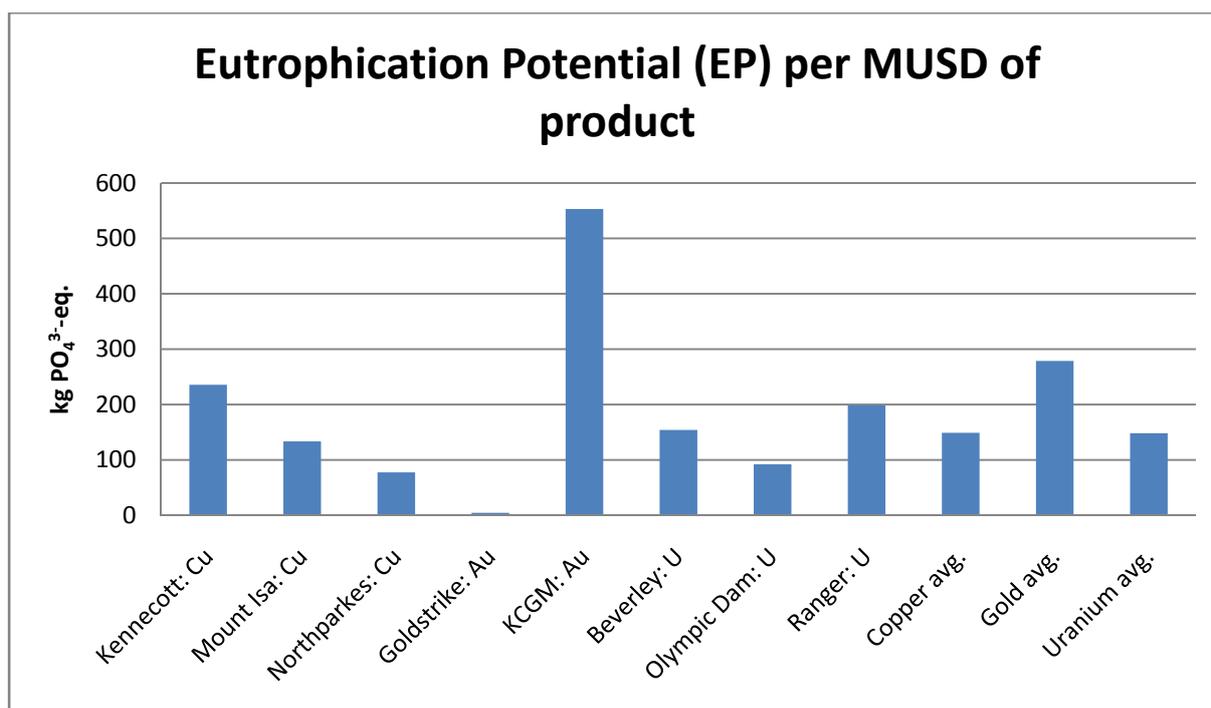


Fig. 16: Eutrophication potential in kg PO₄³⁻-equivalents per MUSD of product.

10.11 Radiation

The uranium mines are the only ones for which doses of ionizing radiation are reported. Selected data collected about effective occupational radiation doses and effective doses to the public are summarised in *Tab. 4*.

Mine	Effective doses (mSv/year)			
	Occupational doses			Doses to the public
	Average	Group of workers receiving the highest dose	Maximum individual dose	
Beverley	0,28		3,46	0,01
McArthur River/Key Lake	1,04	2,5	10,2	0,1 - 0,001
McClellan Lake	0,39		3,76	0,1 - 0,001
Olympic Dam		4,1	8,1	0,026
Rabbit Lake	1,5	5,5	12,6	0,1 - 0,001
Ranger		1,3	5,1	0,003
Rössing		4,7		

Tab. 4: Occupational doses of ionizing radiation and doses to the public (for references please refer to Appendix III: References to Primary Data).

In Australian uranium mines, doses are typically reported for designated workers, defined as workers who may receive a dose greater than 5 mSv per year (Australian Government 2003). Designated workers belong to “Group of workers receiving the highest dose” in *Tab. 4* above. In Canadian uranium mines, doses are reported for different categories of workers such as “Underground miner” and “Mill worker”. The dose of the group of workers receiving the highest dose in Canadian uranium

mines is the dose reported in the “Groups of people receiving the highest dose”-column in *Tab. 4*. Thus, doses reported in that column are not directly comparable since the figures for designated workers include a larger group of people. Average figures sometimes also include office workers, which significantly lower the average. These reported figures can be compared with other figures of effective occupational doses as in *Tab. 5*, below and with the figure of worldwide annual average background sources of 2.4 mSv (UNSCEAR 2000).

	Source/ practice	Number of monitored workers (thousands)	Average annual effective dose (mSv)
Man made sources	Nuclear fuel cycle (incl. uranium)	800	1.8
	Industrial uses of radiation	700	0.5
	Defence activities	420	0.2
	Medical uses of radiation	2 320	0.3
	Education/veterinary	360	0.1
	Total man made sources	4 600	0.6
Enhanced natural sources	Air travel (crew)	250	3
	Mining (other than coal)	760	2.7
	Coal mining	3 910	0.7
	Mineral processing	300	1
	Above ground workplaces (radon)	1 250	4.8
	Total natural sources	6 500	1.8

Tab. 5: Background radiation sources (adopted from UNSCEAR (2000))

With a few exceptions, the reported doses are in comparison relatively low, especially doses to the public. Relating this with epidemiological studies on groups exposed to ionizing radiation we can only attempt to assess the health impacts from uranium mining activities. Such studies have estimated that people exposed to a total dose of 100 mSv have a 10 percent higher risk of dying of non leukaemia cancer and a 19 percent higher risk of dying of leukaemia than people not exposed to that dose (Analysgruppen vid KSU 2006). Consequently, in the worst case scenario, if the same person is exposed to doses in the region of the maximum reported individual dose each year, the worker would be exposed to a total dose of 100 mSv after ten years. This hypothetical dose of 100 mSv is then achieved during a period of time that is the double of those recommendations made by ICRP,

which recommends that the total dose shall not exceed 100 mSv over a period of five years (ICRP 1991).

10.12 Tailings

A general discussion of the tailings dilemma connected to the different operations is presented below. By using a simplified reasoning, the amounts of tailings generated, the type of ore, the metals usually connected to the specific type of ore, process chemicals and water conditions (mainly in the form of precipitation) will be compared.

10.12.1 Waste Quantities Generated

Not all mining companies report the amount of mine waste generated. The waste was therefore calculated using the production quantities and ore grades. The result is visualized in Fig. 17.

As expected, gold mines produce the most waste owing to the low ore grade. The gold grade of the mines in this study ranges between 0.00016% at Navachab to 0.00066% at Vaal River operations.

If not considering McArthur’s remarkably high ore grade, the copper mines have the highest average ore grade of the compared objects, ranging from 0.54 to 3.42%. The variation in mineral grade for the uranium mines in this report is extremely large. Rössing, with the lowest ore grade, has a grade of 0.028%, while the figure of MacArthur is 19 %. However, the ore grade at McArthur is somewhat remarkable, since the remaining mines have an ore grade between 0.028-0.69%. The extremely high ore grade at McArthur is the reason why the uranium mines produce less waste than copper operations.

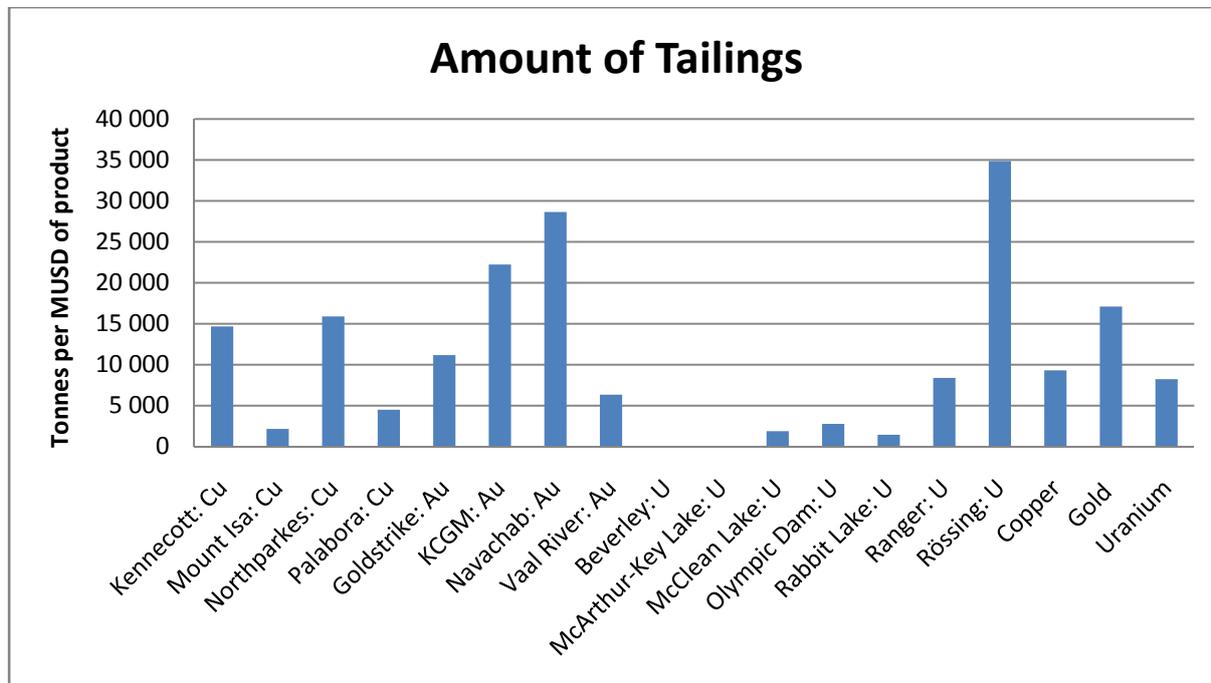


Fig. 17: Amounts of tailings in tonnes per MUSD of product.

10.12.2 Performance Assessment

The parameters chosen for the analysis are specified for each operation in *Tab. 6*.

Operations	Mineral mined	Ore grade (%)	Waste quantities (t/MUSD)	Main ore minerals	Water assets and precipitation	Main leach chemical
Kennecott	copper	0.54	15 000	sulphides	High	(flotation chemicals)
Mount Isa	copper	3.42	2 200	sulphides, (carbonates)	Low	(flotation chemicals)
Northparkes	copper	1.4	16 000	sulphides	Average	(flotation chemicals)
Palabora	copper	0.7	4 500	sulphides, (oxides, phosphates, silicates)	Average	(flotation chemicals)
Goldstrike	gold	0.0004	11 000	sulphides	Low	cyanide
KCGM	gold	0.0002	22 000	sulphides	Low	cyanide
Navachab	gold	0.00016	29 000	schist, sulphides	Low	cyanide
Vaal River	gold	0.00066	6 300	sulphides	Low	cyanide
McArthur-Key Lake	uranium	19.05	43	oxides	High	acid
McClellan Lake	Uranium	0.45	1 900	?	High	sulphuric acid
Olympic Dam	uranium	0.07	2 800	oxides, sulphides	Low	sulphuric acid
Rabbit Lake	uranium	0.69	1 450	oxides, (silicates)	High	sulphuric acid
Ranger	uranium	0.12	8 400	schist, silicified carbonates	High	sulphuric acid
Rössing	uranium	0.0289	35 000	oxides, silicates	Low	sulphuric acid

Tab. 6: Summary of Performance Assessment parameters.

The most common combinations of parameters for each mineral are presented in *Tab. 7* to serve as a base for the following reasoning. The column for the type of mineral describes the minerals most commonly associated to Au, Cu and U in the operations investigated. The sulphide minerals at Olympic Dam ore will also be discussed; due to the strong connection between sulphide minerals and acid mine drainage.

Mineral mined	Average annual tailings quantities (t/MUSD)	Type of ore minerals	Water abundance	Contained metals and substances	Process chemicals	Environmental impact
Gold	17 000	sulphide	low	As, Cd, Pb, Zn etc	Cyanide	- Rel. low AMD potential. - Cyanide - Heavy Metals
Copper	9 300	sulphide	low		(flotation chemicals)	- Rel. low AMD potential
			high			- High AMD potential - Heavy metals
Uranium	8 200	sulphide	low	As, Cd, Pb, Zn, U, Ra, Th etc	Sulphuric acid	- Rel. low AMD , - Radiation
		oxide	low	U, Ra, Th etc		- No AMD potential, - Radiation
			high			- No AMD potential, - Radiation

Tab. 7: General Performance Assessment approach.

10.12.2.1 Copper

Copper is exclusively extracted from sulphide ores and the precipitation is similar to Scandinavian conditions, except for Mount Isa. Thus, there is a great risk of acid mine drainage and related releases of heavy metals. Metals commonly present in sulphide ores are primarily arsenic, cadmium, copper, iron and zinc.

With less precipitation and as well as buffering carbonates present in the ore, the acid mine drainage potential of the mine waste from Mount Isa Mine, should be lower than for the other copper mines.

The Palabora ore contains silicates that might also have buffering capacity that can mitigate acid mine drainage.

10.12.2.2 Gold

Similarly to copper, sulphide minerals host most of the gold of this study and it is connected to the same heavy metals as the copper ores. The acid mine drainage connected to the investigated gold mining operations is expected to be of lower gravity due to the relatively dry climate at all sites.

A greater problem is instead the use of cyanide. The free form of cyanide will decay in the tailings but WAD complexes with metals common in sulphide minerals, e.g. copper, cadmium and zinc, can be released, posing potentially severe environmental threats.

In dry areas, cyanide in tailings is more problematic than otherwise because animals are more attracted to the water present in the tailings management facility.

10.12.2.3 Uranium

Uranium is generally mined from oxide ores. At Olympic Dam, the uranium is extracted from sulphide ore and at Ranger, schist is the mineral connected to the uranium mined. A majority of the mines are located in areas with a good access to water but for example Rössing in Namibia operates in an arid area. Besides uranium, radioactive elements, such as radon and radium, can be hazardous to both environment and humans, which has been treated in chapter 5.

Oxide minerals are neutral in water, hence problems of acid mine drainage are not applicable in the same way for uranium. The water conditions are therefore not as crucial in this case. Nevertheless, radiological concerns connected to tailings issues remain a problem.

At Olympic Dam, sulphide ores are mined. Hence, there is a risk of acid mine drainage and the subsequent leaching and transportation of heavy metals. However, the risk is somewhat decreased due to the dry climate.

10.13 Summarised Results

The two following graphs (Fig. 18 & Fig. 19) summarise the average results for most of the parameters in this investigation.

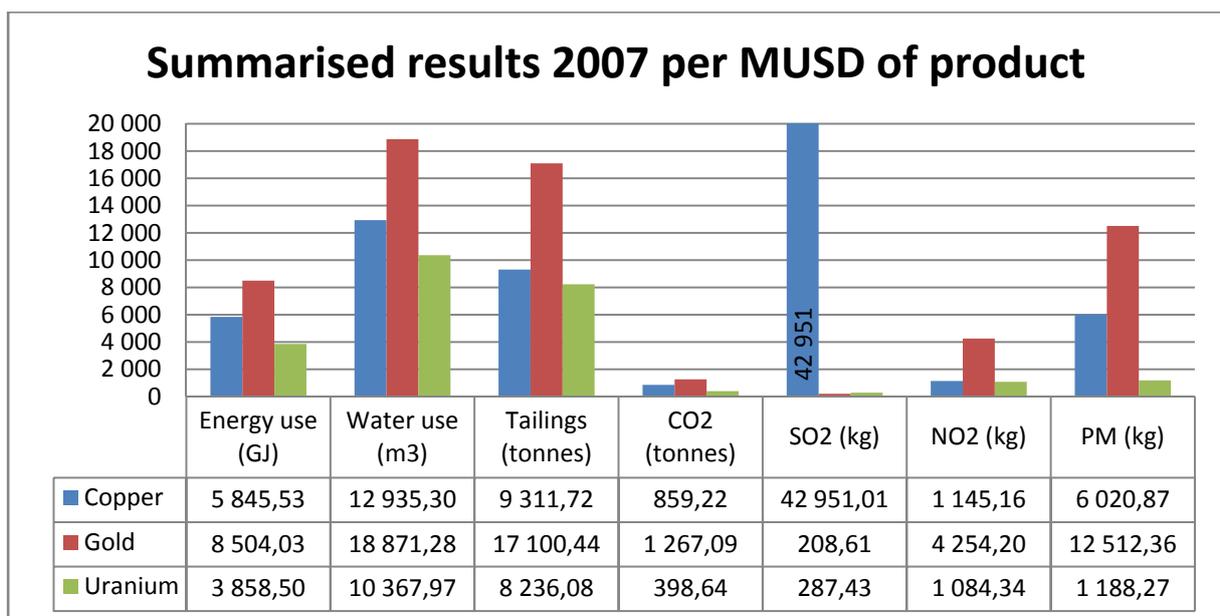


Fig. 18: Summarised results I for year 2007.

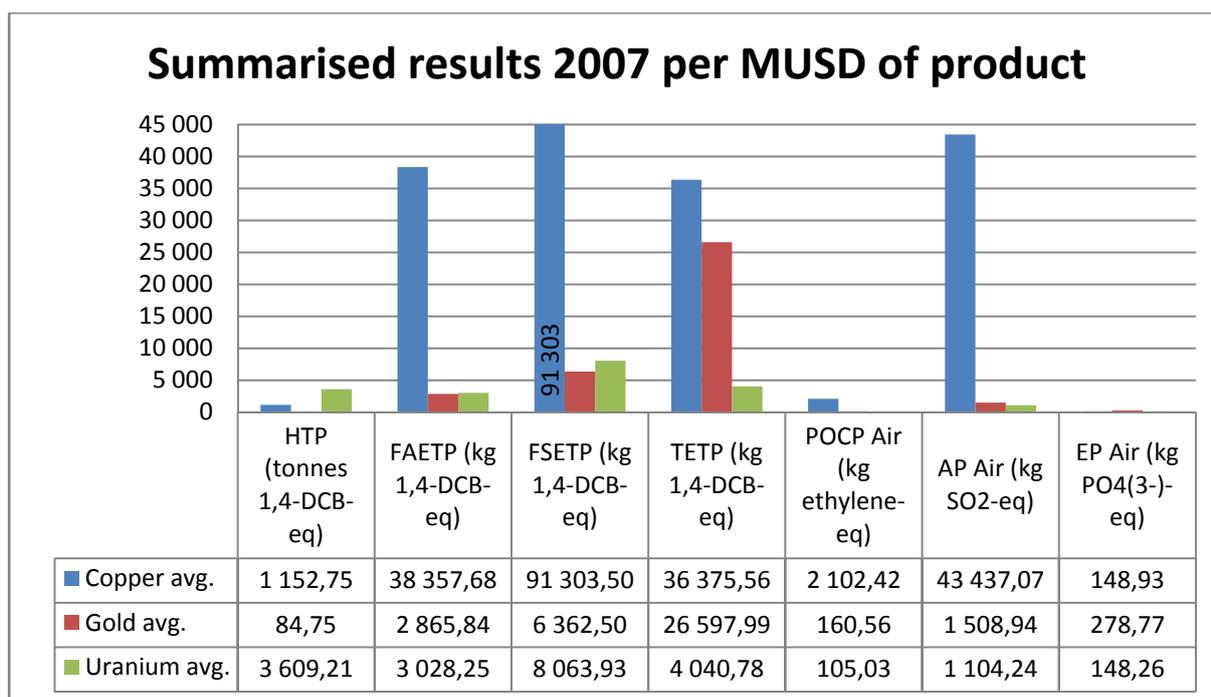


Fig. 19: Summarised results II for year 2007.

10.14 Robustness of Results

Since the economic value of the production is the functional unit of this study, the robustness of the results primarily needs to be analysed with respect to this parameter. Prices on the investigated minerals have increased during the past five years and using the Metal Prices page on infomine (Infomine: Metal Prices 2008) the metal prices five years ago were determined. *Tab. 8* below shows approximate mineral prices five years ago and the prices used in this study and the relative change during this period. As can be observed, the prices of copper and gold have witnessed a similar increase while the increase of gold price has been somewhat more modest.

Mineral	Approximate Price November 2003	Price used in this study (avg. 2007)	Unit	Increase
Copper	2 000	7 139	USD/tonne	257%
Gold	400	696	USD/troy ounce	74%
Uranium	13	45	USD/lb	246%

Tab. 8: Mineral prices in a five year perspective.

Using price levels five years ago, the results are quite different, which can be observed in *Fig. 20* and *Fig. 21*. In general, the uranium mining industry still performs well but the results are most significantly changed for the gold mining industry, which shows better performances in relation to current results. This is most probably related to the fact that the price on gold has been more stable. Five years ago, the value of current production was relatively smaller for copper and uranium compared to today and consequently, all impacts are more severe per economic value. However, since the mineral prices most likely reflect the production, it is not reasonable to believe that the current production would be the same five years ago.

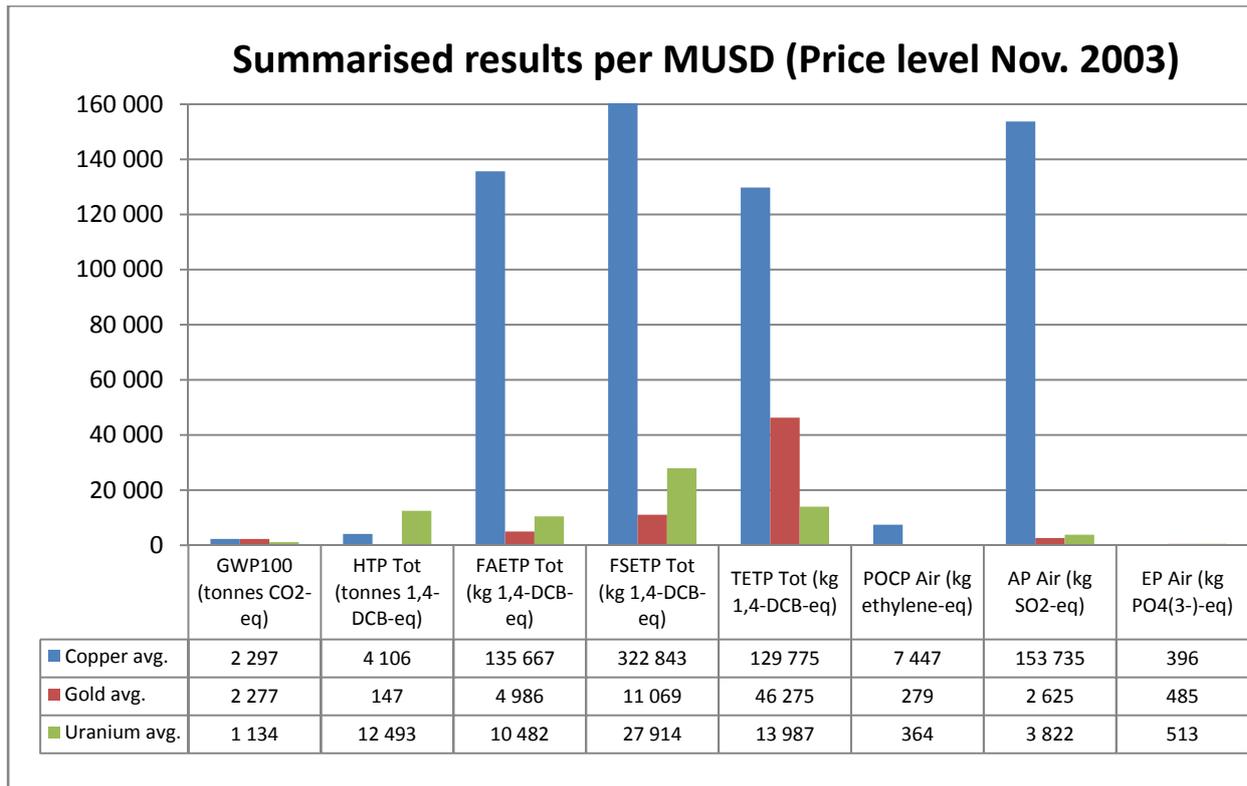


Fig. 20: Summarised results I per MUSD of product with November 2003 price levels.

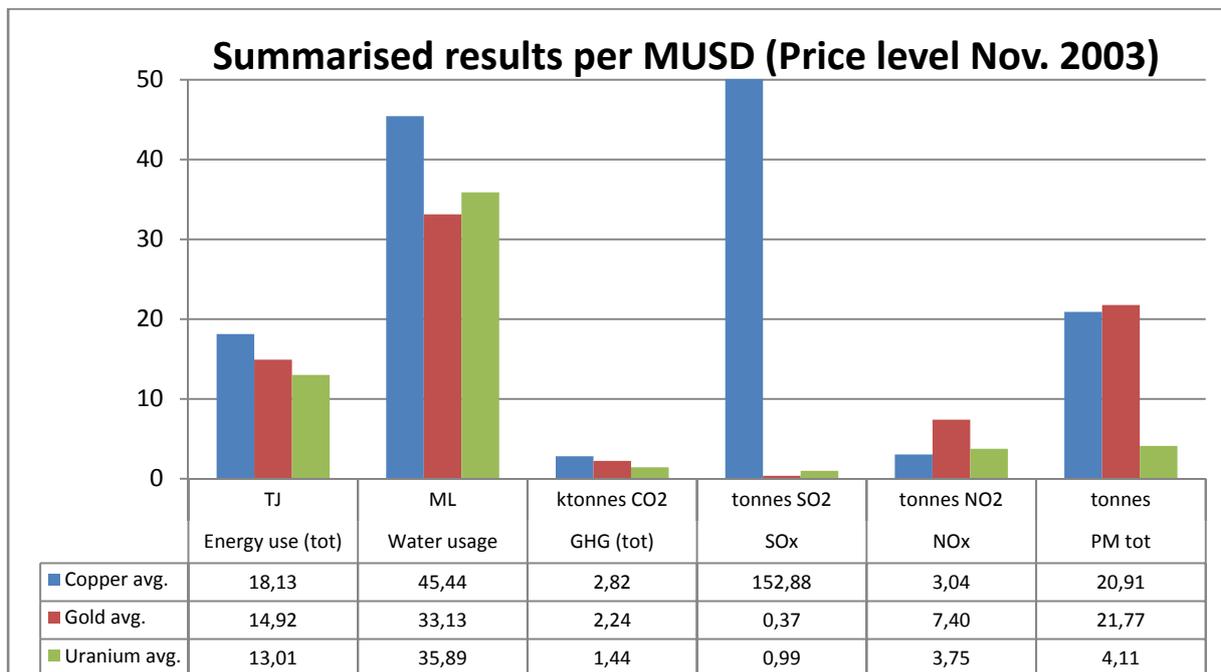


Fig. 21: Summarised results II per MUSD of product with November 2003 price levels.

One uncertainty about the results concerns the missing characterisation factors. But even after setting relatively high hypothetical values for the missing characterisation factors, the relative results remain unchanged.

11 Conclusion

The purpose of this investigation is to determine whether or not uranium mines, from an environmental point of view generally perform better or worse than any other mineral mining industry. Comparing environmental performance and health aspects in the mining industry is a broad and extensive task and based on the findings of this report it is impossible to come to an unequivocal conclusion that is valid for the entire industry. However, based on the parameters investigated in this study, the relative performances of the three minerals can be used to conclude something in this specific case.

Considering all parameters subject to investigation, human toxicology, radiation and lost time injury frequency rate issues are the only ones showing a negative result for the uranium mining industry, in relative terms. These three areas are typically categorized under health aspects, which is one of the topics of this study. However, the main effects contributing to the unfavourable result in the human toxicology impact for uranium mines originate from Olympic Dam operations, which is a multi mineral operation where copper accounts for about 75% of total sales. This study has not been able to determine whether the operations responsible for the release of the toxic substances at Olympic Dam can be allocated to the entire operations or to any specific mineral. Radiation is a more unambiguous parameter that is solely related to uranium mining in this study. It is estimated to be primarily an occupational issue since the reported doses to the public are very low.

In all other investigated aspects, the uranium mining industry shows a very good relative performance, generally positioned as the best or tied leader of the investigated minerals. All these areas of analysis can be categorized as contributing to environmental impacts.

Finally, the most complex but also among the most important areas concern mine waste and tailings issues. Based on the highly restricted amount of data and information available about the area, only some general conclusions can be drawn. The three different minerals can generally be connected to some specific impacts of special importance to each mine. Acid mine drainage generally appears to be a problem primarily for the copper mining industry but also in the case of gold due to their occurrence in sulphide mineral ores. For the mining and extraction of gold, one issue of special importance is that of cyanide management. The uranium mining industry has to deal with long-term radiological issues from tailings management facilities. Furthermore the amount of tailings, and consequently also the land area required for its storage is highly related to the mineral grade. Therefore, the highest amounts of tailings are commonly encountered in the gold mining industry.

With the knowledge and information gained and collected during the course of this thesis, and based on the parameters included in this study, it can be concluded that the uranium mining industry is connected to more adverse potential impacts to the human health compared with other mines of this investigation. From an environmental point of view however, including resource consumption, the uranium mining industry is associated with impacts that are significantly lower than the worst average mineral, in each parameter, of this study.

12 Discussion

The choice of an appropriate functional unit for this study, when comparing completely different commodities such as gold, copper and uranium, is not obvious. Besides the functional unit chosen, that is the value of the product when crossing the system boundaries, the amount of ore mined and the amount of product produced were also discussed and analysed briefly. When the functional unit was changed to tonnes of product, gold with the lowest ore grade became far worse than the other minerals in all categories. Uranium, associated with the highest average ore grade benefited from the change in functional unit. When comparing performance using the amounts of ore mined, gold improved vastly while the competitiveness of uranium decreased. However, most important when looking at resource consumption and impacts on society and environment should be to compare it with the value provided by the products and consequently by the operations. There is not always a clear distinction between what is classified as ore mined and waste rock, resulting in large uncertainties regarding reported data. Further, the degree of refinement varies between the different minerals but also between different sites. Hence, the economic value of the product is judged to represent the most useful functional unit.

A large number of data has been interpreted and analysed throughout the project. The quality and amount of data has influenced the results and conclusions. Companies report different data in different ways and in varying detail. Additionally, the databases from NPI and NPRI, providing data of emissions do not have the same criteria for reporting. Further, the amount and type of data available has limited what aspects to study. There are more impact categories of interest when comparing the different operations, such as ozone depletion potential and land use to mention some of them. The lack of some characterisation factors could also have influenced the calculations of impact categories. Cyanide is a substance that likely would have changed the results if a characterisation factor existed. Human toxicity and ecotoxicity potential are controversial areas that are often the subject to discussions and disagreement.

A dilemma worth discussing more explicitly is the allocation of resource consumption and emissions from operations producing more than one type of mineral and the subsequent analysis of the results. Especially Olympic Dam is troublesome, due to the fact that the largest part of the production and sales is connected to copper production and not uranium. At all other operations, only minor amounts of additional minerals are produced. At Olympic Dam, copper represents as much as 75% of sales. Allocation with respect to share of sales was considered the most appropriate since specific and detailed data connected to the different mineral operations did not exist. The same method has been used by Mudd and Diesendorf (2007), investigating the sustainability of uranium mining and milling. Even though one might discuss the appropriateness in treating Olympic Dam as a uranium mine, it was included since it is the largest uranium deposit in the world.

Tailings and tailings management are important areas that were only covered briefly in this study. The discussions and conclusions were drawn using an extremely simplified picture of a complex interaction between several factors. There are more aspects to include in an analysis of this sort and the actual performance and properties of the objects studied should be extended beyond the current system boundaries.

The original goal was to be able to draw general conclusions of the impact of mining uranium, copper and gold, using data from specific operation. This study can hopefully offer an indication of such a comparison. However, for general conclusions to be made, the number of objects investigated

should be greater in order to decrease the influence of individual sites. With a larger number of objects, the national influences as well as the corporate role in results could perhaps have been studied and analysed further.

13 Recommendations on Further Studies

The allocation of emissions and resource consumption to a specific mineral in multi mineral mines has been discussed and it is an area which can be studied further. The current approach of economic allocation does not take into account processes that are linked to one mineral only. Based on the limited amount of information available for this study it was judged to be the most appropriate solution but a more in depth analysis of the different mining methods and processes and their contribution to the environmental loads of the different operations would be interesting. This is particularly interesting for Olympic Dam and its extremely high emissions of polycyclic aromatic hydrocarbon, contributing to the unfavourable results connected to human toxicity potential.

The problems connected to tailings are very important and complex and they could be studied far more in depth than what was possible in this report. Even with a more thorough analysis however, the problem to compare and value problems such as acid mine drainage and radioactive tailings leachate remains. A tool for an evaluation and comparative study of that sort is recommended.

Depending on where the different operations are located, the companies struggle with different environmental and social problems. For example HIV and AIDS are extremely important issues in the African countries and thus also important for the companies with operations in this part of the world. These companies have acknowledged the severity of the disease and appear to work actively with prevention and medical aid. How mining operations affect indigenous people, e.g. the aborigines in Australia, is another local aspect. For future studies, a wider sustainability perspective can be used in order to incorporate these aspects.

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Appendix I: Primary Raw Data

BEVERLEY MINE - Heathgate				
	Raw data	Unit	Adapted figures	Changed unit
Production				
Mineral produced	748	tonnes U3O8	748	tonnes
Mineral grade	0,18	%	0,18	%
Energy use				
		4*1 MW, 1*2 MW, NG generators		
<i>see consumption of diesel and NG</i>	3,5	between 3 and 4 kg U3O8 per GJ NG used		GJ
Diesel	24897,6	GJ (Diesel (tonnes)*45,6 GJ/tonnes (see conversion))	24897,6	GJ
NG (primary energy not converted to electrical energy)	217080	GJ (NG (tonnes)*45GJ/tonnes (see conversion))	217080	GJ
Total	241977,6		241977,6	GJ
Employees				
	148		148	#
	297	(From which radiation data is collected)		
Water usage				
	136	ML (GAB-water)	136000	m3
	20	ML/day (Namba aquifer +/- 0 0,2%)		
	3000	kg U3O8/ML GAB		
Chemicals				
Diesel	546	tonnes	546	tonnes
Natural gas	4824	tonnes	4824	tonnes
GHG-emissions				
from Diesel	1825,03516	tonnes (GJ/1000*emission factor (tCO2/TJ)*oxidation factor)	1825,03516	tonnes CO2-ekv
from NG	12330,9157	tonnes (GJ/1000*emission factor (tCO2/TJ)*oxidation factor)	12330,9157	tonnes CO2-ekv
Total	14155,9509	tonnes	14155,9509	tonnes CO2-ekv
Health				
Radiation	0,28	mSv (Average employee dose)	0,28	mSv
	3,46	mSv (Maximum employee dose)	3,46	mSv
Dust				
LTFIR	17,5	between 15 and 20 per 1000000 hours worked	3,5	/200000h

Environmental Impacts and Health Aspects in the Mining Industry

Land disturbance				
used area	8	km2 (mineral lease)	800	ha
rehab. And decommissioning fund	7633000	\$ AUS	9125551,73	USD
Waste				
Waste	125	tonnes (low level radioactive waste)	125	tonnes
Waste water	81,9	ML year ended June 2006 (injected back into wells)	81900	m3
Waste water	2,6	L/s (annualised mean rate)		

Environmental Impacts and Health Aspects in the Mining Industry

GOLDSTRIKE - Barrick				
	Raw data	Unit	Adapted figures	Changed unit
Production				
Ore mined (calculated from Mineral produced and mineral grade)	11552370,31	tonnes	11552370,31	tonnes
Mineral produced	1630000	ounces	46,209685	tonnes
Mineral grade	0,128	ounces/ton	0,000400002	%
Energy use				
	4901551	GJ (direct)	4901551	GJ
	3707828	GJ (indirect)	3707828	GJ
	801	MJ/tonne of ore processed		
Employees	1600	# (employees)	1600	#
	200	# (contractors)	200	#
Water				
Water usage	11519723	m3 water consumed by mining and processing	11519723	m3
	1072	liter/tonne of ore processed		
Chemicals				
Leach chemicals - cyanide etc	4747	tonnes cyanide used	4747	tonnes
Explosives used	13621	tonnes	13621	tonnes
Emissions				
GHG-emissions	1193202	tonnes CO2-ekv	1193202	tonnes
Sox				tonnes
Nox				tonnes
Health				
LTFIR	0,6	/200000h	0,6	/200000h
Land disturbance				
Disturbed	2978	ha	2978	ha
Reclaimed	339	ha	339	ha
Total footprint	3317	ha	3317	ha
Waste				
Waste	373	tonnes (Offsite Hazardous Solid Waste Disposal)	373	tonnes
	50492	litres (Offsite Hazardous Liquid Waste Disposal)	50492	litres

KCGM - Barrick & Newmont				
	Raw data	Unit	Adapted figures	Changed unit
Production				
Total movement (entire KCGM)	78,71	Mtonnes	78710000	tonnes
of which ore	12,68	Mtonnes	12680000	tonnes
waste rock	66,03	Mtonnes	66030000	tonnes
Mineral produced in Fimiston Mill	0,63	Mounces gold bullion	17,860185	tonnes gold bullions
Mineral grade	2,01	g/t	0,000201	%
Energy use				
Purchased Electricity (Natural Gas)	384 556	MWh	1384401,6	GJ
LPG (non-transport)	3247	kL	83447,9	GJ
Automotive Gasoline (Petrol)	50,05	kL	1711,71	GJ
Automotive Diesel	72 230	kL	2788078	GJ
Employees				
	588	#	588	#
Additional contractors	465	#	465	#
Water				
	8769	ML water is used, see table below for type and amounts of water.	8769000	m3
Water consumed by mining and processing	6026000	m3	6026000	m3
Chemicals				
Explosives used	18304	tonnes	18304	tonnes
Cyanide use	783	tonnes	783	tonnes
Emissions				
GHG-emissions	584 690	tonnes CO2-eq	584 690	tonnes CO2-eq
LTFIR	0,1	Lost-Time Injury Rate – the number of work-related injuries that result in days away from work for every 200,000 hours worked.	0,1	LTI per 200 000 h
Land disturbance				
Used area in total	1600	ha in total land disturbed and rehabilitated by KCGM since 1989 (approx figure from graph)	1600	ha
Used area - pit area	2,7	km2		
Rehabilitated land	36,1	ha rehab. In 2007	36,1	ha
Total amount of rehabilitated land from start	700	ha, approx. Figure of rehab. land since 1989.	700	ha
Area	460	ha	460	ha
Waste rock	66,03	tonnes	66,03	tonnes

Greenhouse gas emissions Table for 2007 from Annual env.al repor, page 45				
Energy Type	Use	Units	Estimated Emissions*	
Purchased Electricity			(tonnes CO2- e)	
Purchased Electricity (Natural Gas)	384 556	MWh	381 479	
Stationary Energy			(tonnes CO2-e)	
LPG (non-transport)	3247	kL	5 000	
Transport Energy			(tonnes CO2-- e)	
Automotive Gasoline (Petrol)	50,05	kL	113	
Automotive Diesel	72 230	kL	195 021	
Waste			(tonnes CO2-- e)	
HFC Coolant (Antifreeze)	323	kL	26	
Explosives	18 304	t	3 051	
Gross emissions (tonnes CO2- e)			584 690	
Emissions as calculated using 'AGO Emissions Calculator'				
Water type	Quantity (ML)	Percentage of Use		
Potable water				
Fimiston Mill	1251	69,1		
Gidji Roaster	429	23,7		
Fimiston Open Pits	112	6,2		
Mt Charlotte	16	0,9		
Rehabilitation	2	0,1		
Effluent water				
Fimiston Mill	612	5		
Saline Water				
Fimiston Mill	6502	85,6		
Gidji Roaster	209	2,7		
Fimiston Open Pits	887	11,7		
Total	8769			

Environmental Impacts and Health Aspects in the Mining Industry

KENNECOTT UTAH COPPER - Rio Tinto					
	Raw data	Unit	Adapted figures	Changed unit	Reference unit
Sales					
- total sales	3546	\$million	3546000000	2017917434	USD
- net profit	1625	\$million	1625000000	924736556,9	USD
Production					
Ore mined (calculated value based on ore grade of Cu and copper cathode production)	49185185,2	tonnes	49185185,19	27989746,95	tonnes
Grade of ore	0,54	% Cu	0,54	0,54	%
	0,32	g/t Au	0,000032	0,000032	%
	2,59	g/t Ag	0,000259	0,000259	%
Mineral produced					
- copper	265600	metric tonnes cathodes	265600	265600	tonnes
- gold	522800	troy oz	16,26089767	16,26089767	tonnes
- silver	4365000	troy oz	135,7666762	135,7666762	tonnes
- molybdenum	14906	metric tonnes cathodes	14906	14906	tonnes
Energy use	21040000	GJ onsite usage and purchased power	21040000	11973204,4	GJ
Employees					
- employees	1815	#	1815	1815	#
- contractors	1200	# approximations (try homepage for more details)	1200	1200	#
Total at site	3015		3015	3015	#
Freshwater consumption	4255	ML	4255000	2421387,107	m3
Emissions					
GHG-emissions	1,9	total million tonnes of CO2 -eq, based on the total onsite and purchased power	1900000	1081230,436	tonnes
Sox	3695	short tons	3352,0301	1907,535245	tonnes
Nox	6654	short tons	6036,37572	3435,112184	tonnes
Particulate matter	3682	short tons (estimated emissions - see the Utah division of Air Quality for precise numbers)	3340,23676	1900,824025	tonnes
Health					
LTFIR	0,41	occurrence of LTI per 200 000 hours worked	0,41	0,41	/200000h
Land disturbance					
Used area	5262	ha (land disturbed for mining, processing and related activities that is not currently rehabilitated)	5262	2994,439238	ha

Environmental Impacts and Health Aspects in the Mining Industry

Rehabilitated land	3749	ha (land disturbed for mining that was later rehabilitated. The object is to manage land with minimum disturbance and to rehabilitate disturbed land as soon as practicable.)	3749	2133,43837	ha
Tailings - area	9200	acres	3723,24	2118,779162	ha
Total volume					
Total mass					
Calculated amount of tailings Using ore grade and Production figures			48904527,16	27830033,27	tonnes
Waste					
Waste generation - mineral	6503	million tonnes (the portion of mines geological resources that is not shipped from the operation as product nor generated by processing activities)	6503000000	3700653433	tonnes
Waste generation - non mineral	0,255	million tonnes (includes industrial and workshop wastes, scrap steel, tires and municipal waste)	255000	145112,5058	tonnes

Environmental Impacts and Health Aspects in the Mining Industry

	MCARTHUR - CAMECO		KEY LAKE - CAMECO		TOTAL	
	Raw Data	Unit	Raw Data	Unit	Total	Unit
Production						
Ore mined	59642	tonnes of ore with average grade of 14.24% U3O8 produced			59642	tonnes
Ore milled	44038	dry tonnes ore milled			44038	tonnes
Ore shipped	44367	dry tonnes ore shipped to Key lake			44367	tonnes
Grade of ore	19,05	% U3O8			19,05	%
Mineral produced (U3O8)	18718337	lbs of U3O8	8488740	kg U3O8	8488,74	tonnes
Mineral grade	19,35	% high grade ore reamed				
	0,53	% low grade ore reamed				
	0,97	% development low grade				
	14,24	% average treated				
Uranium produced			7198452	kg U		
Ore leached (diluted with stockpiled ore from mined out pits)			211806	dry tonnes ore leached	211806	tonnes
Grade of ore leached (mill head grade)			4,07	%U3O8 (mill head grade)	4,07	%
Ammonium sulphate fertilizer			12991	tonnes ammonium sulphate fertilizer	12991	tonnes
Energy use						
Electricity	350265,1169	GJ (2006) multiply with production factor below to get data for 2007	504095	GJ (2006) multiply with production factor below to get data for 2007	826147,85	GJ
Fossil Fuel	235788,336	GJ (2006) multiply with production factor below to get data for 2007	229918	GJ (2006) multiply with production factor below to get data for 2007	450328,006	GJ

Environmental Impacts and Health Aspects in the Mining Industry

Total	586053,4529	GJ (2006) multiply with production factor below to get data for 2007	734013	GJ (2006) multiply with production factor below to get data for 2007	1276475,86	GJ
Employees	715	#	1102	#	750	#
	750	# (McArthur River + Key Lake total)	750	# (McArthur River + Key Lake total)		
Water						
Amount of water released from treatment plant	2399616	In 2007, the McArthur River Operation discharged 2,399,616 m3 of treated effluent to the receiving environment.			3952484	m3
Water usage	122793	m3 from toby lake potable water intake	10468961	m3 (total inflow to Key Lake)	10591754	m3
Treated mill effluent			1552868	m3 (treated mill effluent released)		
Chemicals				mera finns i table 3.2		
Barium Chloride	85200	kg	367200	kg	452400	kg
Ferric Sulphate	429560	kg			429560	kg
Lime	35907	kg	20583020	kg lime	20618927	kg
Sulphuric Acid	51253	kg			51253	kg
Sulfur			11162952	kg sulphur	11162952	kg
Acid			46231000	kg acid	46231000	kg
Emissions						
Particulate matter PM10	4,2	tonnes PM10	33	tonnes PM10	37,2	tonnes
PM2,5	0,99	tonnes PM2.5	0,209	tonnes PM2.5	1,199	tonnes
Total	6,5	tonnes total particulate matter	250	tonnes total particulate matter	256,5	tonnes
GHG-emissions						
	81855	tonnes CO2-ekv (2006) multiply with production factor below to get data for 2007	89450,9	tonnes CO2-ekv (2006) multiply with production factor below to get data for 2007	165649,119	tonnes CO2

Environmental Impacts and Health Aspects in the Mining Industry

Total direct	21991	tonnes CO2-ekv (2006) multiply with production factor below to get data for 2007	31077,3	tonnes CO2-ekv (2006) multiply with production factor below to get data for 2007	51315,9042	tonnes CO2
Total indirect	59864	tonnes CO2-ekv (2006) multiply with production factor below to get data for 2007	58373,6	tonnes CO2-ekv (2006) multiply with production factor below to get data for 2007	114333,215	tonnes CO2
Sox			258	tonnes SO2	258	tonnes SO2
Nox	32	Tonnes NO2	64	Tonnes NO2	96	tonnes NO2
Ammonia			84	tonnes ammonia	84	tonnes
VOC			481	tonnes volatile organic carbon	481	tonnes
Health						
Radiation (average both sites)	1,5	mSv (average)	0,58	mSv (average effective dose)	1,04	mSv
Highest average dose (underground miner)	2,5	mSv (underground miner, highest average dose)	1,35	mSv (highest average effective dose, mill operations)	2,5	mSv
Highest maximum dose (undeground support)	10,2	mSv (underground support, maximum dose)	5,24	mSv (max effective dose, mill maintenance)	10,2	mSv
LTFIR (average)	1	LTI 2007 per how many hours	0,49	/200000 h worked	0,745	/200000h
Urine test		1 of 3387 samples had U conc above 5 µg/l				
Land disturbance						
rehabilitated land	81,1	"ha (Agronomic and Native Grass Revegetation				
1998-2005 McArthur River Operation)"			81,1	ha		
	2,5	ha (Tree/Shrub Seedling Revegetation 2007 McArthur River Operation)			2,5	ha
Tailings						
area			45	ha (AGTMF)	45	ha

Environmental Impacts and Health Aspects in the Mining Industry

Total volume (waste & tailings)* accumulated			17771155	m3 (waste and tailings) accumulated	17771155	m3
Total mass (waste & tailings)* accumulated			8471467	tonnes (waste and tailings) accumulated	8471467	tonnes
Mass 2007			248702	tonnes 2007 (waste and tailings)	248702	tonnes
Waste					0	m3
Clean waste	5325	m3			5325	m3
Domestic waste	2750	m3			2750	m3
Contaminated garbage	6075	m3			6075	m3
Mineralised waste to Key Lake	111857	tonnes			111857	m3

MCCLEAN LAKE - Areva				
	Raw data	Unit	Adapted figures	Changed unit
Sales	1900000	Cpd		
Production				
Total movement	2973436	m3	2973436	m3
Ore mined				
- Total from Sue ore	193503	tonnes	193503	tonnes
- from Sue E ore	190921	tonnes	190921	tonnes
U-grade in ore mined art Sue E	0,49	%	0,49	%
Mineral recovered from mining	933918	kg	933,92	tonnes
Mill feed	170083	tonnes	170083	tonnes
mineral grade in mill feed	0,45	% U	0,45	% U
Recovery rate mill	94,7	% U	94,7	% U
Mineral recovered after processing	732952	kg U in U3O8	864,36	tonnes U3O8
Mineral shipped	732097	kg U in U3O8 shipped	863,36	tonnes U3O8
Employees	314	#	314	#
Water usage	1393575	m3	1393575	m3
Amount of water released from treatment plant	"JEB WTP: 1 333 435 m3,			
Sue WTP: 1 091 884 m3 "		2425319	m3 in total	
Energy use				
From fossil fuels	572 906	GJ	572906,07	GJ
Power (electric energy)	40625910	kWh	146253,28	GJ
Total energy		GJ	719159,34	GJ
Emissions				
Particulate matter	223,633	tonnes of total particulate matter. Includes PM10 and PM2,5	223,63	tonnes
GHG-emissions (tot)	48403	tCo2-eq	48403,35	tonnes of CO2-eq.
GHG-emissions (direct)	39459	tCo2-eq	39459,41	tonnes of CO2-eq.
GHG-emissions (indirect)	8944	tCo2-eq	8943,95	tonnes of CO2-eq.
Sox	11,346	tonnes (see comments by table of what is included)	11,35	tonnes

Environmental Impacts and Health Aspects in the Mining Industry

Nox	9,871	tonnes (see comments by table of what is included)	9,87	tonnes
Health				
Radiation				
- Mean dose	0,39	mSv in mean radiation dose, for JEB and Sue NEW workers	0,39	mSv in mean radiation dose for JEB and Sue NEW workers
- Maximum dose	3,76	mSV	3,76	mSv
Dust				
LTFIR	1,2	per 200 000 hr	1,2	LTI per 200 000 h
Land disturbance				
Used area -surface Lease, of which	3677	ha	3676,6	ha
- developed	693	ha	692,8	ha
- undeveloped	2984	ha	2983,8	ha
Rehab. And Decommissioning fund	35000000	Cdn \$million in financial insurance	37,6	MUSD in financial insurance
Tailings				
Amount deposited 2007	240280	dry tonnes	240280	dry tonnes
Total amount of existing taling				
- mass	1240026	tonnes	1240026	tonnes
- volume	1209546	m3	1209546	m3
Emissions from Talings				
Annual conc of U in Tailings	0,02	%	0,02	%
Waste				
overburden	202916	m3	202916	m3

MOUNT ISA MINE - Xstrata						
	Raw data	Unit	Allocated to Cu-production	Unit	Adapted figures	Changed unit
Sales						
- Total sales Mount Isa Operations	2353859852	USD		USD	2,4E+09	USD
- copper	1274041835	USD	1274041835	USD	1,3E+09	USD
Share of sales						
- Copper	54,12564533	%		%		
- Zinc	27,27450211	%		%		
- Lead	14,04447005	%		%		
- Silver	4,5553825	%		%		
Production						
Ore mined,						
- copper	6000000	tonnes ore mined	6000000	tonnes ore mined	6000000	tonnes
- Zn-Ag-Pb-ore mineral produced	5,12	Mtonnes		Mtonnes	5,12	tonnes
- copper	172552	tonnes of copper in concentrate	172552	tonnes of copper in concentrate	172552	tonnes copper in concentrate
- ZN	217907	tonnes copper in anodes at smelter, including Ernest Henry	140129,464	tonnes copper in anodes	140129	tonnes copper anode
- Pb	226529	tonnes concentrate				
Mineral grade	125195	tonnes bullion				
	3,42	i.e. copper head grade	3,42	i.e. copper head grade	3,42	%
Energy use						
Electricity (indirect energy)	1100	kWh/tonne contained metal (mount isa op.) (estimated from graph)	153371699	kWh (kWh per tonne contained metal*tonnes Cu-anode*0,995 (99,5% Cu in anodes))	552 138,11	GJ
Diesel	45655000	litres	24711063,4	litres	953 847,05	GJ
LPG (non-transport)	343000	litres	185650,964	litres	4 771,23	GJ
Unleaded petrol	138000	litres	74693,3906	litres	2 554,51	GJ
Total direct energy					961 172,79	GJ

Environmental Impacts and Health Aspects in the Mining Industry

Total ENERGY					1 513 310,90	GJ
Employees						
	4376	total Mount Isa, i.e. also zinc and etc		total Mount Isa, i.e. also zinc and etc		
	2600	# for copper operations, including contractors, approximate number	2600	# for copper operations, including contractors, approximate number	2600	# employees
Water						
Water usage	8023	megalitres of freshwater (total MIM)	4342,50053	megalitres of freshwater (total MIM)	4342501	m3
Chemicals/Materials						
Cement	99708	tonnes	53967,5985	tonnes	5,4E+07	kg
Coke	39075	tonnes	21149,5959	tonnes	2,1E+07	kg
Copper sulphate	4040	tonnes	2186,67607	tonnes	2186676	kg
Explosives	12059	tonnes	6527,01157	tonnes	6527,01	tonnes
Grinding media	21291	tonnes	11523,8912	tonnes	1,2E+07	kg
Lime	12179	tonnes	6591,96235	tonnes	6591962	kg
Limestone	68353	tonnes	36996,5024	tonnes	3,7E+07	kg
Lubricating oils	2894000	litres	1566396,18	litres	1566396	litres
Sodium carbonate	4731	tonnes	2560,68428	tonnes	2560684	kg
Sodium hydroxide	101	tonnes	54,6669018	tonnes	54666,9	kg
Silica	75987	tonnes	41128,4541	tonnes	4,1E+07	kg
Tyres (heavy vehicles)	375	#	202,97117	#	202,971	#
Tyres (light vehicles)	2946	#	1594,54151	#	1594,54	#
Wood	1867	tonnes	1010,5258	tonnes	1010526	kg
Xanathe	2089	tonnes	1130,68473	tonnes	1130685	kg

NAVACHAB - AngloGold Ashanti				
	Raw data	Unit	Adapted figures	Changed unit
Production				
Mining volumes	7,3	Mtonnes	7300000	tonnes
Mineral recovered	80000	oz bullion	2,27	tonnes bullion
After processing recovered grade	1,56	g/t (recovered mineral content per unit of ore treated)	0,000156	%
Attributable Adjusted gross profit	13000000	USD in adjusted gross profit	13000000	USD
Employees	409		409	#
Water				
Water usage	1116821	m3 (m3 water/oz production = 10,91)	1116821	m3 water
Recycled water	446728,4	m3, i.e. 40% of used water	446728,4	m3 water
Energy use (tot)	320275	GJ (GJ energy/oz production = 3,48)	320275	GJ
Energy direct		GJ	163181	GJ
Energy indirect (el.)		GJ	157093	GJ
Chemicals				
- cyanide	1022	tonnes	1022	tonnes
- alkalis	209,5	tonnes	209500	kg
- acids	20,9	tonnes	20900	kg
- Hydrogen	102	tonnes	102000	kg
Peroxides				
- Liquid fossil fuels	4,4	ML	4,4	ML
- Explosives	2028	tonnes	2028	tonnes
Emissions				
Particulate matter				
GHG-emissions (tot)	13267	tonnes of CO2- eq.(CO2e/oz = 0,14)	13267	tonnes CO2-eq.
GHG-emissions (direct)			12077	tonnes CO2-eq.
GHG-emissions (indirect: from el.- prod.)			1190	tonnes CO2-eq.
LTFIR	4,59	per million hours worked	0,92	injuries per 200 000 hrs worked
Land disturbance				
Used area	6152,6	ha	6152,6	ha
Rehabilitated land	493	ha (is included in the 6153,2 ha above)	493	ha (included in the figures above)
Rehab. And Decommissioning fund/liability	3000000	USD	3	MUSD
- for rehab	1500000		1,5	MUSD

- for Decommissioning Rehabilitation cost to date	1500000		1,5	MUSD
Tailings - area - capped Tailingsarea of total	300000	m2	30	ha
Waste Overburden	160000	m2	160000	m2
	7,3	Mtonnes, se also table Ni if interesting	7299988,61	tonnes

NORTHPARKES - Rio Tinto				
	Raw data	Unit	Adapted figures	Changed unit
Production				
Ore mined, alt	2600000	tonnes ore mined	2600000	tonnes
ore processed	5360000	tonnes ore milled	5360000	tonnes
Mineral produced* (concentrate containing gold and silver)	126500	tonnes copper concentrate	126500	tonnes
	86513	oz gold	2,452600294	tonnes
Mineral grade	1,4	% (copper)	1,4	%
	0,4	g/tonnes (gold)	0,00004	%
Energy use				
	889332	GJ	889332	GJ
	7,03	GJ/tonnes of copper concentrate		
	0,158	GJ/tonnes of ore milled		
Employees				
	260	#	260	#
Water				
Water usage	3506	ML tot (water input)	3506000	m3
	2881	ML freshwater consumption	2881000	m3
	5726	water usage (including recycled water)	5726000	m3
	0,027	ML/tonnes of copper concentrate		
	0,65	m3/tonnes of ore milled		
Emissions				
GHG-emissions	189494	tonnes CO2-ekv.	189494	tonnes
	1,49	tonnes CO2-ekv/tonnes of copper concentrate		
	38,8	kg CO2-ekv/tonnes of ore milled		
Health				
LTFIR	2,1	/200000h	2,1	/200000h
AIFR	3,95	/200000h	3,95	/200000h
Land disturbance				
used area	930	ha (disturbed area)	930	ha
	2500	ha (total project site)	2500	ha
Land clearance 2007	17,95	ha	17,95	ha
rehabilitated land 2007	2,7	ha	2,7	ha
Tailings				
area	141	ha (Tailings Dam 1)	141	ha
	137	ha (Tailings Dam 2)	137	ha
tailings tot area	278	ha (TD 1+2)	278	ha

Mass	5000000	tonnes of tailings deposited in 2007	5000000	tonnes
Waste	3116	"tonnes (total) 37.5% decrease from 2006"		
(75% scrap metal, 11% general waste, 8.5% inert material, 3% waste oil)"	3116	tonnes		

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OLYMPIC DAM - BHP Billington					
	Raw data	Unit	Adapted figures, all operations	Allocation to U-production, 20%	Changed unit
Revenue					
	20	% from U			
	75	% from Cu			
	5	% from Au/Ag			
Production					
Ore mined, alt mineral produced	9200000	tonnes	9200000	1840000	tonnes
	3985	tonnes U3O8	3985	3985	tonnes U3O8
	204000	tonnes copper cathodes approximately	204000		tonnes cu cathodes
mineral grade	0,7	kg U3O8/tonnes	0,07	0,07	%
Energy use	5,3	PJ (Total)	5300000	1060000	GJ
Coal and coke	0,3	PJ	300000	60000	GJ
purchased electricity	3,1	PJ	3100000	620000	GJ
Distillate	1	PJ	1000000	200000	GJ
Fuel Oil	0,2	PJ	200000	40000	GJ
Other	0,8	PJ	800000	160000	GJ
Employees	2500	# (about)	2500	2500	#
Water usage	12740	Ml (high quality water, ground water from wells)	12740000	2548000	m3
	320	Ml (low quality water, saline)	320000	64000	m3
	440	Ml (recycled water)	440000	88000	m3
Emissions					
GHG-emissions	1030000	tonnes CO2-ekv	1030000	206000	tonnes CO2-ekv
SOx	1280	tonnes	1280	256	tonnes SO2-ekv
NOx	1180	tonnes	1180	236	tonnes NO2-ekv
Health					
Radiation	4,1	mSv/year (average designated worker)	4,1	4,1	mSv/year (average designated worker)
	8,1	mSv/year (maximum dose)	8,1	8,1	mSv/year (maximum dose)
Dust		Chart 16-1			
TRIFR	13,2	injuries/million man hours	2,64	2,64	injuries/200000h worked
Land disturbance					
used area	1216110	ha (Total footprint)	1216110	243222	ha
infrastrucure	340	ha	340	68	ha

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disturbed by mining (directly)	1180	ha	1180	236	ha
other	690	ha	690	138	ha
area intended for future operations	15790	ha	15790	3158	ha
buffer zones (not intended for operations)	1197690	ha	1197690	239538	ha
rehabilitated land	430	ha	430	86	ha
land owned in biodiversity rich area for biodiversity conservation purposes	7340	ha	7340	1468	ha
Tailings					
mass	8356710	tonnes	8356710	1671342	tonnes
other hazardous mineral waste	1340	tonnes	1340	268	tonnes
Waste					
Waste	6350	tonnes generated (total)	6350	1270	tonnes
	160	tonnes of which recycled	160	32	tonnes
	6190	tonnes of which disposed on landfill	6190	1238	tonnes
Waste oil	350000	litres (generated in total (all sent for recycle/reuse/burning off site))	350000	70000	litres

Environmental Impacts and Health Aspects in the Mining Industry

PALABORA, Rio Tinto				
	Raw data	Unit	Adapted figures	Changed unit
Production				
Ore mined	11850000	tonnes	11850000	tonnes
- copper concentrate delivered to smelter	70443	tonnes	70443	"tonnes
- Supplementing copper concentrate, purchased from Chambasi and Fosker	43605	tonnes		
- copper anode	90700	tonnes	90700	tonnes
recovery rate mill	93,6	%	93,6	%
mineral recovered after processing	91659	tonnes copper cathod	91659	tonnes copper cathod
ore grade	0,7	% copper in ore hoisted	0,7	%
sales	1861000000	rand	13128832214	USD
earnings/profit	58	milion US\$	58000000	USD
Employees	1955	permanent employees	1955	# permanent
	126	fixed term employees	126	# fixed term
Water				
Water usage	10444	MI (intake+rainfall+from dewatering and seepage capturing)	10444000	m3
recycled water	25168	MI	25168000	m3
Energy use tot	6482888	GJ	6482888	GJ
indirect (electricity)	678608	MWh	2442988,8	GJ
direct (fossil)		substraction	4039899,2	GJ
Emission				
GHG-emissions tot	985706	tonnes CO2-eq	985706	tonnes CO2-eq
GHG-emissions (direct)		tonnes CO2-eq	342854,26	tonnes CO2-eq
GHG-emissions (indirect)		tonnes CO2-eq	642851,74	tonnes CO2-eq
Sox	22839	tonnes	22839	tonnes
Health				
Dust	21	microgram/m3/year	21	microgram/m3/year
LTFIR	0,32	per 200 000 h worked	0,32	per 200 000 h worked
Land disturbance				
used area	119000	m2	11,9	ha
rehab. And decommissioning fund/liability	312000000	rand	2201,07	MUSD

Tailings - mass	14,7	million t	14700000	tonne
Calculated amount of tailings using ore grade and production figures			2948542,71	tonnes
Non-mineral waste, 2007				
Oil recycled:	206	kl	206000	litres
Wood recycled:	57	t	57	tonne
Metal recycled:	2728	t	2728	tonne
Domestic waste:	675	t	675	tonne
Hazardous waste:	44	t	44	tonne
Ash:	3607	t	3607	tonne
Mineral waste				
Slag	242	kt	242000	tonne
Vermiculite waste rock	1217	kt	1217000	tonne

RABBIT LAKE - Cameco				
	Raw data	Unit	Adapted figures	Changed unit
Production				
Ore mined	191470	tonnes	191470	tonnes
total haulage (ore+waste+special waste)	282016	tonnes	282016	tonnes
recovery rate mill	96,7	%	96,7	%
mineral recovered after processing	4000000	lbs U3O8	1814,36948	tonnes
mineral recovered after processing	1814360	kg U3O8	1814,36	tonnes
"mineral grade in mill feed Average mill head grade (% U3O8)"	0,69	%	0,69	%
Employees	466	#	466	
839, acc to 6,9, 466, p 8-1 922, table 6.9.1.1-1				
Water				
Water usage	4171622	m3 (total inflow)	4171622	m3
The total quantity of water discharged to the environment via Weir No.3 (Station 2.3.3) was 3,783,667 m3 in 2007.	3783667	m3 (5-2, see also table 5.3.1 for water balance)	3783667	m3
water pumped from pit	1421387	m3	1421387	m3
Energy use				
Electricity	493763,9	GJ (2006) multiply with production factor below to get data for 2007	430470,5406	GJ
Fossil Fuel	293009,3	GJ (2006) multiply with production factor below to get data for 2007	255449,7641	GJ
Total	786773,2	GJ (2006) multiply with production factor below to get data for 2007	685920,3047	GJ
Emissions				
GHG-emissions	105435,3	tonnes CO2-ekv (2006) multiply with production factor below to get data for 2007	91920,02613	tonnes
total direct	31043,5	tonnes CO2-ekv (2006) multiply with production factor below to get data for 2007	27064,17425	tonnes
total indirect	74391,8	tonnes CO2-ekv (2006) multiply with production factor below to get data for 2007	64855,85188	tonnes
Health				
Radiation	1,5	mSv (average)	1,5	mSv
	5,5	mSv (underground miner, highest average dose)	5,5	mSv
	12,6	mSv (underground miner, maximum dose)	12,6	mSv

LTFIR		Cameco's year-end combined lost-time frequency for employees and long-term contractors was below target at 0.7 per 200,000 hours worked (vs. target of 0.8)....in report p 8-1: lost time accidents in 2007=7		
Tailings				
amount deposited 2007	292401	tonnes	292401	tonnes
total amount of existing tailings				
- mass	6740000	tonnes 1984- tom2007	6740000	tonnes
- area	142012	m2	14,2012	ha
waste from mines	50196	tonnes	50196	tonnes
"special waste from mines (0,03%U or more)"	40350	tonnes	40350	tonnes

RANGER - Rio Tinto & ERA				
	Raw data	Unit	Adapted figures	Changed unit
Sales				
Total sales	357080000	\$ AUD	426903185,1	USD
Net profit	76089000	\$ AUD	90967392,33	USD
Production				
Ore mined, alt	2900000	tonnes ore mined	2900000	tonnes
ore processed	1900000	tonnes ore milled	1900000	tonnes
mineral produced	5412	tonnes U3O8	5412	tonnes
mineral grade	0,12	%	0,12	%
Energy use (tot)	1222980	GJ	1222980	GJ
Direct (in report)	17709	GJ	17709	GJ
Indirect (as stated for 2006)	20934662	litres diesel fuel	829012,6152	GJ
Employees				
	419		419	#
Water usage	650	ML freshwater	650000	m3
Chemicals				
Emissions				
GHG-emissions	17,7	tonnes CO2 ekv/tonnes UO produced 2006		
	741	tonnes additional GHG emissions 2007		
	4748	tonnes U3O8 production 2006		
	84039,6	total tonnes CO2-ekv 2006 (17.7*4748)		
Direct	84780,6	total tonnes CO2-ekv 2007 (84039.6+741)	84780,6	tonnes CO2-ekv
Indirect	60767,99256	tonnes CO2 (GJ diesel*73,67*0,995)	60767,99256	tonnes CO2-ekv
Total	83109	tonnes CO2	83109	tonnes CO2-ekv
Sox	120	tonnes SO2	120	tonnes SO2
Health				
Radiation	1,3	mSv (240 designated workers, 0.6 mSv for the rest)	1,3	mSv
Health	5,1	mSv max 2006	5,1	mSv
LTFIR	0,3	/200000h (estimated from graph)	0,3	/200000h
AIFR	1	/200000h (estimated from graph)	1	/200000h
Land disturbance				
used area	520	ha (79 km2 total land lease)	520	ha

rehabilitated land rehab. And decommissioning fund	79	km2 (total land lease)	7900	ha
	48088000	\$ AUD	57491095,46	USD

RÖSSING - Rio Tinto 69%				
	Raw data	Unit	Adapted figures	Changed unit
Net profit	979000000	N\$ (after/tax)	6900791517	USD
Production				
Ore mined, alt	21396000	tonnes mined rock	21396000	tonnes
ore processed	12613000	tonnes ore processed	12613000	tonnes
mineral produced	3046	tonnes U3O8	3046	tonnes
mineral grade	0,289	kg/tonnes of U3O8	0,0289	%
Energy use, total	1533981	GJ	1533981	GJ
Diesel for mobile equipment	769810	GJ	769810	GJ
Diesel for roaster	19968	GJ	19968	GJ
Petrol	17853	GJ	17853	GJ
Purchased electricity	726350	GJ	726350	GJ
Employees	1175	#	1175	#
Water				
amount of water released from treatment plant	3050000	m3 seepage water collected	3050000	m3
Water usage	3299980	m3	3299980	m3
	0,26	m3/tonnes of ore milled		
	900	m3/tonnes of U3O8 produced (estimated from graph)		
GHG-emissions				
total	197029	tonnes	197029	tonnes CO2-ekv
total excl. Electricity	90296	tonnes	90296	tonnes CO2-ekv
Diesel from mobile equipment	57047	tonnes	57047	tonnes CO2-ekv
Diesel used at roaster	1480	tonnes	1480	tonnes CO2-ekv
Petrol	1176	tonnes	1176	tonnes CO2-ekv
Extraction process	27748	tonnes	27748	tonnes CO2-ekv
Blasting of explosives	2573	tonnes	2573	tonnes CO2-ekv
Sewage plant	227	tonnes	227	tonnes CO2-ekv
Sodium carbonate	21	tonnes	21	tonnes CO2-ekv

Environmental Impacts and Health Aspects in the Mining Industry

Waste in landfill plants	24	tonnes	24	tonnes CO2-ekv
Purchased electricity	106733	tonnes	106733	tonnes CO2-ekv
Sox	24	tonnes	24	tonnes SO2
Nox	1152	tonnes	1152	tonnes NO2
Health				
Radiation	4,7	mSv (workers in Final Product Recovery, lowest working group; 1.2 mSv offices)	4,7	mSv
Dust	0,92	mg/m3 (fine crushing plant)	0,92	mg/m3
LTFIR	0,71	/200000h	0,71	/200000h
AIFR	0,71	/200000h	0,71	/200000h
Land disturbance used area				
	20	km2		
	2395	ha	2395	ha
rehab. And decommissioning fund	91000000	N\$ (Rössing Environmental Rehabilitation Trust Fund)	641442316,7	
decommissioning cost	800000000	N\$ estimated 2007	5639053333	
Tailings - if not already treated				
area	730	ha	730	ha
mass	879	Mtonnes	879000000	tonnes
Waste				
Waste rock	21396000	tonnes (waste rock)	21396000	
Domestic/Industrial	445	tonnes landfill (on site)	445	
Low level radioactive	698	tonnes landfill (on site)	698	
Contaminated Grease	37	tonnes hazardous waste site (off site)	37	
Scrap metal	2296	tonnes recycled (off site)	2296	
Paper	71	tonnes recycled (off site)	71	
Wood	46	tonnes recycled (off site)	46	
Used synthetic oil	134	tonnes recycled (off site)	134	
Used mineral oil	715	tonnes recycled (on site)	715	

Environmental Impacts and Health Aspects in the Mining Industry

Used tyres	50	tonnes stored (on site)	50	
Fluorescent lighting tubes	40	tonnes stored (on site)	40	

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VAAL RIVER - AngloGold ashanti						
	Raw data	Unit	Allocated to AU-production	unit	Adapted figures	Changed unit
Production						
ore treated/miled (not including surface operations)	5,5	Mt (note, this is with surface operations)	5	Mt (note, this is with surface operations)	5139484,49	tonnes
- ore from surface operations	8	Mtonnes	7	Mtonnes	7475613,8	tonnes
treated/milled mineral recovered after processing						
- gold	35267	kg gold	35267	kg gold	35,27	tonnes
- uranium	1,23	million pounds of uranium oxid	1,23	million pounds of uranium oxid		
produced in Great Noligwa, Kopanang and Tau Lekoa						
recovered grade	6,59	g/t, (recovered mineral content per unit of ore treated) average value of Val river operations	6,59	g/t, (recovered mineral content per unit of ore treated) average value of Val river operations	0,000659	%
Attributable adjusted gross profit	121	M USD	113	M USD	113068658,7	USD
Employees, of which	18954	#	p. 40	#	p. 40	#
- employees	15871	#	15871	#	15871	#
- contractors	3084	#	3084	#	3084	#
Water						
amounts used	17217443	m3 (m3 water/oz prod. = 11,58)	16088869	m3	16088869,31	m3
Energy use	7365629	GJ (GJ/oz prod = 5,33)	6882825	GJ	6882824,72	GJ
Chemicals						
- cyanide	3917812	kg (kg cyanide/oz gold=2,76)	3917812	kg (kg cyanide/oz gold=2,76)	3917,81	tonnes
Emissions						
GHG-emissions	1848984	tonnes of CO2eq (Coeq/oz gold = 1,34)	1727786	tonnes of CO2-eq	1727786,29	tonnes of CO2-eq.
SOx	339	tonnes	317	tonnes	316,78	tonnes
Health						

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LTFIR	14,54	LTI per Mh	14,54	LTI per Mh	2,91	LTI per 200 000 h
FIFR (fatal injury frequency rate)	0,29	FI per Mh	0,29	FI per Mh	0,06	FI per 200 000 h
Land use						
Rehabilitated land	349	ha	326	ha	326,12	ha
rehab. And decommissioning fund/liability	77,5	M USD	72	M USD	72,42	M USD

EPA-TRI	Goldstrike		Kennecott Utah Copper
	Air tot (lbs)	Air tot (lbs)	Water tot (lbs)
Substances			
Ammonia	29299	4000	
Antimony & compounds	2		250
Arsenic	321	5	250
Benzene			
Beryllium & compounds			
Boron & compounds			
Cadmium & compounds	11		250
Carbon disulfide			
Carbon monoxide			
Chlorine	15		
Chromium (III) compounds	63	250	250
Chromium (VI) compounds			
Cobalt & compounds	1		
Copper & compounds	21	1000	1210
Cresol -			250
Cumene (1-methylethylbenzene)			
Cyanide (inorganic) compounds	1510	750	250
Dioxine - (grams)	0,1145	0,402	
Ethylbenzene			
Ethylene glycol -			
Fluoride compounds			
Formaldehyde (methyl aldehyde)			
Hydrochloric acid (acid aerosols)		4824	
Lead & compounds			
Magnesium oxide fume			
Manganese & compounds	165	6	510
Mercury & compounds			
Nickel & compounds	49	250	2600
Nickel carbonyl			
Nickel subsulfide			
Nitrate -			250
Nitric acid	2		
Oxides of Nitrogen			
Particulate Matter 10.0 um			
Polychlorinated dioxins and furans			
Polycyclic aromatic hydrocarbons			
Selenium & compounds	37	250	250
Silver compounds -	6	1	250
Sulfur dioxide			
Sulphuric acid (H2SO4)			
Thallium compounds -	1		250
Toluene (methylbenzene)			
Total VOC			
Vanadium compounds	4	67	250

Xylenes (individual or mixed isomers)			
Zinc and compounds	69	255	1210

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NPI - Facility	ERA Ranger Mine				Heathgate				Kalgoorlie CGM Super Pit/Fimiston Open Pit			
	01-Jan-2006 to 31-Dec-2006				01-Jul-2006 to 30-Jun-2007				01-Jul-2006 to 30-Jun-2007			
Substance	Total (kg)	Air	Land	Water	Total (kg)	Air	Land	Water	Total (kg)	Air	Land	Water
Ammonia (total)												
Antimony & Compounds									28	28	0	
Arsenic & compounds	11	8,3	0,81	1,6	14	6	8		410	400	2,2	
Benzene	250	250							300	300		
Beryllium & compounds	18	17	0,49	0,69	0	0	0		4,4	4,4	0	
Boron & compounds									81	81	0	
Cadmium & compounds	0,57	0,13	0,19	0,25	0	0	0		2	2	0	
Carbon disulfide												
Carbon monoxide	3E+05	3E+05			54000	54000			6E+05	6E+05		
Chlorine												
Chromium (III) compounds	200	190	2	3,1	110	69	41		1500	1500	0	
Chromium (VI) compounds					0	0						
Cobalt & compounds	62	57	4	0,62					340	340	0	
Copper & compounds	1200	1200	11	4,5	46	30	16		2300	760	1600	
Cresol												
Cumene (1-methylethylbenzene)	3,3	3,3										
Cyanide (inorganic) compounds									26000	25000	320	
Dioxine												
Ethylbenzene	4,4	4,4							9,1	9,1		
Ethylene glycol												
Fluoride compounds	0	0			290	200	90		4800	4800	0	
Formaldehyde (methyl aldehyde)									27000	27000		
Hydrochloric acid					0	0						
Lead & compounds	51	30	19	1,9	76	35	41		67	67	0	
Magnesium oxide fume					0	0						
Manganese & compounds	560	200	230	130					14000	14000	0	
Mercury & compounds	0,44	0	0,19	0,25	0	0	0		570	560	1,7	
Nickel & compounds	190	180	7	1,8	140	49	88		550	550	0	
Nickel carbonyl					0	0						
Nickel subsulfide					0	0						
Nitrate												
Nitric acid												
Oxides of Nitrogen	8E+05	8E+05			88000	88000			2E+06	2E+06		
Particulate Matter 10.0 um	8E+05	8E+05			3E+05	3E+05			5E+06	5E+06		
Polychlorinated dioxins and furans	0,3	0,3			0	0						
Polycyclic aromatic hydrocarbons	3,9	3,9			2,5	2,5			19	19		
Selenium & compounds									2,3	2,3	0	

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Silver compounds												
Sulfur dioxide	1E+05	1E+05			800	800			6300	6300		
Sulfuric acid	1600	1600			0	0						
Thallium compounds												
Toluene (methylbenzene)	120	120						180	180			
Total Volatile Organic Compounds	44000	44000			12000	12000		1E+05	1E+05			
Vanadium compounds												
Xylenes (individual or mixed isomers)	140	140						83	83			
Zinc and compounds	220	140	81	4,4				2400	850	1600		
Source												

Environmental Impacts and Health Aspects in the Mining Industry

NPI - Facility	Mount Isa Mine				Northparkes				Olympic Dam			
	01-Jul-2006 to 30-Jun-2007				01-Jul-2006 to 30-Jun-2007				01-Jul-2006 to 30-Jun-2007			
Substance	Total (kg)	Air	Land	Water	Total (kg)	Air	Land	Water	Total (kg)	Air	Land	Water
Ammonia (total)	8800	0,01	8700	58					15	15		
Antimony & Compounds	26000	26000	13	0,27	7	7						
Arsenic & compounds	75000	74000	59	12	74	74			1100	1100		
Benzene	220	220							210	210		
Beryllium & compounds	980	960	22		4	4			9,5	9,5		
Boron & compounds	13000	7400	5800		170	170						
Cadmium & compounds	4200	4000	230	3,6	3,4	3,4			37	37		
Carbon disulfide	1200	1200	15						400	400		
Carbon monoxide	8E+05	8E+05			31000	31000			4E+05	4E+05		
Chlorine	8	8										
Chromium (III) compounds	91	90	0,34		490	490			1800	1800		
Chromium (VI) compounds					0	0			0,41	0,41		
Cobalt & compounds	9500	8800	650		130	130			88	88		
Copper & compounds	4E+05	4E+05	53000	490	15000	15000			11000	11000		
Cresol												
Cumene (1-methylethylbenzene)					0,11	0,11			0,03	0,03		
Cyanide (inorganic) compounds	10000	10000	17						670	670		
Dioxine												
Ethylbenzene	0,75	0,75							0,54	0,54		
Ethylene glycol												
Fluoride compounds	30000	5200	25000		2200	2200			2100	2100		
Formaldehyde (methyl aldehyde)												
Hydrochloric acid									4500	4500		
Lead & compounds	3E+05	3E+05	450	170	290	290			4800	4800		
Magnesium oxide fume					0	0			68	68		
Manganese & compounds	30000	7800	23000	32	7800	7800			4000	4000		
Mercury & compounds	940	940	0,01		0,53	0,53			16	16		
Nickel & compounds	3300	3200	180	1	270	270			870	870		

Nickel carbonyl												
Nickel subsulfide												
Nitrate												
Nitric acid					0	0			0	0		
Oxides of Nitrogen	2E+06	2E+06			97000	97000			1E+06	1E+06		
Particulate Matter 10.0 um	4E+06	4E+06			2E+06	2E+06			3E+06	3E+06		
Polychlorinated dioxins and furans	5E-07	5E-07			0	0			0	0		
Polycyclic aromatic hydrocarbons	0,53	0,53			1,2	1,2			37000	37000		
Selenium & compounds	7,3	6,1	0,96	0,22	23	23						
Silver compounds												
Sulfur dioxide	2E+08	2E+08			3200	3200			1E+06	1E+06		
Sulfuric acid									9700	9700		
Thallium compounds												
Toluene (methylbenzene)	5,4	5,4							89	89		
Total Volatile Organic Compounds	1E+05	1E+05			7900	7900			81000	81000		
Vanadium compounds												
Xylenes (individual or mixed isomers)	14	14							33	33		
Zinc and compounds	5E+05	4E+05	5500	120	810	810			840	840		
Source												

Appendix II: Characterisation Factors

Impact Category:	Human toxicity, HTP (inf. global) (kg 1,4-DCB-eq./kg)			Photo-oxidant formation, POCP (in kg ethylene-eq./kg)			Acidification, AP (in kg SO ₂ - eq./kg) Generic factors			Eutrophication, EP (in kg PO ₄ (3-)-eq./kg)		
	Air	Freshwater	Soil (agricultural)	Air	Freshwater	Soil (agricultural)	Air	Freshwater	Soil (agricultural)	Air	Freshwater	Soil (agricultural)
Unit:												
Ammonia	0,1	x	x				1,88			0,35		
Antimony	6700	5100	8900									
Arsenic	35000	950	3200									
Benzene	1900	1800	15000	0,218								
Beryllium	23000	14000	13000									
Boron												
Cadmium	15000	23	20000									
Carbon disulfide	2,4	2,4	3,6									
Carbon monoxide				0,027								
Chlorine												
Chromium III	650	2,1	5100									
Chromium VI	3400000	3,4	8500									
Cobalt	17000	97	2400									
Copper	4300	1,3	94									
Cresol												
Cumene (isopropyl benzene)				0,5								
Cyanide												
Dioxine												
Ethylbenzene	0,97	0,83	0,75	0,73								
Ethylene	0,64	0,65	0,78	1								
Flouride												
Formaldehyd	0,83	0,037	2,3	0,519								
Hydrochloric acid	0,5	x	x				0,88					
Lead	470	12	3300									
Magnesium oxide fume												
Manganese & compounds												
Mercury	6000	1400	5900									
Nickel	35000	330	2700									
Nickel carbonyl	35000	330	2700									

Environmental Impacts and Health Aspects in the Mining Industry

Nickel subsulfide	35000	330	2700								
Nitrate									0,1		
Nitric acid						0,51			0,1		
Oxides of nitrogen	1,2	x	x	0,028		0,7			0,13		
Particulate matter (Dust (PM10))	0,82	x	x								
Polychlorinated dioxins and furans											
Polycyclic aromatic hydrocarbons (Carcinogenic PAH)	5,70E+05	280000	71000	0,8	average aromatics						
Selenium	48000	56000	29000								
Silver											
Sulfur dioxide	0,096	x	x	0,048		1					
Sulphuric acid						0,65					
Tallium	430000	230000	2000000								
Toluene	0,33	0,3	0,35	0,637							
Total VOC				0,416	average VOC						
Vanadium	6200	3200	19000								
Xylene (orto-, meta-, para-)	0,0633333	0,37	3,9333333	1,056667							
Zinc	100	0,58	64								

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Impact Category: Ecotoxicity, ETP (inf. Global) (kg 1,4-DCB-eq./kg)									
Unit:	FAETP			FSETP			TETP		
Substance				Air	Freshwater	Soil (agricultural)	Air	Freshwater	Soil (agricultural)
Ammonia	x	x	x	x	x	x	x	x	x
Antimony	3,7	20	10	9,1	48	24	0,61	1,70E-20	1,3
Arsenic	50	210	130	130	530	340	1600	1,00E-17	330
Benzene	0,000084	0,091	0,00072	0,000064	0,07	5,40E-04	0,000016	0,000014	3,40E-03
Beryllium	17000	91000	46000	20000	11000	54000	1800	3,30E-16	3600
Boron									
Cadmium	290	1500	780	740	3900	2000	81	1,40E-20	170
Carbon disulfide	0,033	110	0,34	0,027	86	0,28	0,0051	4,80E-03	1,6
Carbon monoxide									
Chlorine									
Chromium III	1,9	6,9	5,3	4,9	18	13	3000	2,30E-19	6300
Chromium VI	7,7	28	21	20	71	54	3000	2,30E-19	6300
Cobalt	640	3400	1700	1100	5600	2800	110	2,70E-18	220
Copper	220	1200	590	560	2900	1500	7	4,10E-21	14
Cresol									
Cumene (isopropyl benzene)									
Cyanide									
Dioxine									
Ethylbenzene	0,00013	0,55	1,80E-03	0,000087	0,36	1,20E-03	1,4E-06	1,20E-06	1,90E-03
Ethylene	1,40E-11	0,022	1,10E-09	9,00E-12	0,014	7,10E-10	1,30E-12	1,10E-12	2,30E-09
Flouride									
Formaldehyd	8,3	280	15	4,5	150	7,9	0,94	1,60E-03	5,8
Hydrochloric acid	x	x	x	x	x	x	x	x	x
Lead	2,4	9,6	6,5	6,2	25	17	16	4,80E-22	33
Magnesium oxide fume									
Manganese & compounds									
Mercury	320	1700	850	810	4400	2200	28000	9,30E+02	56000
Nickel	630	3200	1700	1600	8300	4300	120	1,00E-18	240
Nickel carbonyl	630	3200	1700	1600	8300	4300	120	1,00E-18	240
Nickel subsulfide	630	3200	1700	1600	8300	4300	120	1,00E-18	240

Environmental Impacts and Health Aspects in the Mining Industry

Nitrate									
Nitric acid									
Oxides of nitrogen	x	x	x	x	x	x	x	x	x
Particulate matter (Dust (PM10))	x	x	x	x	x	x	x	x	x
Polychlorinated dioxins and furans									
Polycyclic aromatic hydrocarbons (Carcinogenic PAH)	170	28000	58	560	89000	190	1	2,10E-03	6,3
Selenium	550	2900	1500	640	3400	1700	53	1,60E-17	110
Silver									
Sulfur dioxide	x	x	x	x	x	x	x	x	x
Sulphuric acid									
Tallium	1600	8000	4200	3900	20000	11000	340	3,10E-17	700
Toluene	0,00007	0,29	1,10E-03	0,00005	0,21	7,50E-04	0,000016	1,40E-05	0,019
Total VOC									
Vanadium	1700	9000	4700	4100	21000	11000	670	1,00E-17	1400
Xylene (orto-, meta-, para-)	0,000066	0,57	0,001933	4,67E-05	0,39	0,001353	8,27E-07	7,63E-07	0,002633
Zinc	18	92	48	46	240	120	12	2,50E-21	25

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