

Nonferrous metals

Zinc – Gold

A reference book for the Industry

Promotion of Benchmarking Tools for Energy Conservation in Energy Intensive Industries in China

Energy Efficiency Component

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Disclaimer

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Beijing, 2009

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Summary and Acknowledgments

As part of the BMT-Tool set (BMT = Benchmarking – Monitoring – Targeting) this reference book for the nonferrous industry provides a short introduction to this industrial sector. After a general introduction of the nonferrous industry, which comprises a big group of metals, special focus was laid only on zinc production and on gold processing. The later is a contribution to the trial to perform a case study on energy benchmarking in the gold industry, which figured out at least to be impossible to perform in face of the secret character of this business. However, it is hoped that the industry experts of this sector might draw some benefit from reading through this paper.

Such a short paper can provide only an overview and highlight major aspects of the industry and applied processes and related consumptions of energy and other environmental aspects. The main information was extracted from open sources in the internet, which can easily be completed by “googeling” in the web. A recommended literature is the “Reference Document on Best Available Techniques in the Non Ferrous Industry (BREF)” published by the Integrated Pollution Prevention and Control (IPPC) Board of the European Commission (2001), which comprises more information, if not on gold, but on zinc and other nonferrous metals to a huge extent.

It has to be noted that this reference book cannot answer all questions related with energy efficiency/intensity in the zinc and gold industry. In fact, these industries could be generally described as energy intensive. But in practice other environmental issues of this industry are more in the spotlight, such as waste water, chemicals and hazardous wastes. Therefore, it is rather difficult to find qualified information on energy consumption related to distinct processes, energy efficient technologies, and energy practices and usage within this industry. Therefore, it is difficult to present energy consumption values associated with the use of BAT. The ranges of energy consumption shown in this reference book for zinc should only be taken as an indication about the approximate need of energy at energy efficient factories. And there are no external energy benchmarks for the gold industry available at all.

Besides this it is hoped that this reference book will be of some guide towards more energy efficiency in the industry.

1 Introduction

1.1 Nonferrous metals

Nonferrous metals and nonferrous alloys are not based on iron and include alloys of aluminum, copper, titanium, zinc, nickel, cobalt, and tungsten, precious metals like gold and refractory metals. Nonferrous metals and nonferrous alloys are useful in many applications because of their versatility, high density, and tensile strength. For example, tantalum sheet metal is used frequently to create surgical instruments because it does not react with bodily fluids and is corrosion resistant. Some nonferrous metals and nonferrous alloys are highly combustible and volatile, including powder zirconium, which may be stored under water for safety, and beryllium oxide, which is highly toxic if inhaled. Welding zirconium is also available. Nonferrous metals and nonferrous alloys are useful for applications requiring nonmagnetic, lightweight, high strength compounds. Since nonferrous metals and nonferrous alloys have high melting points, they are also often used in electrical and electronic applications.

1.2 Nonferrous metals industry

Non-ferrous metals are produced from a variety of primary and secondary raw materials. Primary raw materials are derived from ores that are mined and then further treated before they are metallurgically processed to produce crude metal. The treatment of ores is normally carried out close to the mines. Secondary raw materials are indigenous scrap and residues and may also undergo some pre-treatment to remove coating materials.

Ore deposits containing metals in viable concentrations in Europe have been progressively depleted and few indigenous sources remain. Most concentrates are therefore imported from a variety of sources worldwide.

Recycling constitutes an important component of the raw material supplies of a number of metals. Copper, aluminum, lead, zinc, precious metals and refractory

metals, among others, can be recovered from their products or residues and can be returned to the production process without loss of quality in recycling. Overall, secondary raw materials account for a high proportion of the production, thus reducing the consumption of raw materials and energy.

The product of the industry is either refined metal or what is known as semis or semi manufactures, i.e. metal and metal alloy cast ingots or wrought shapes, extruded shapes, foil, sheet, strip, rod etc.

The structure of the industry varies metal by metal. No companies produce all non-ferrous metals although there are a few companies producing several metals, e.g. copper, lead, zinc, cadmium etc.

The size of the companies producing metals and metal alloys varies from a few employing more than 5000 people and a large number having between 50 and 200 employees.

Ownership varies between international and national metals groups, industrial holdings groups, stand-alone public companies and private companies.

Some metals are essential as trace elements but at higher concentrations are characterised by the toxicity of the metal, ion or compounds and many are included under various lists of toxic materials. Lead, cadmium and mercury are of the greatest concern.

1.3 Environmental issues

The main environmental issues for the production of most non-ferrous metals from primary raw materials are the potential emission to air of dust and metals/metal compounds and of sulphur dioxide to if roasting and smelting sulphide concentrates or using sulphur-containing fuels or other materials. The capture of sulphur and its conversion or removal is therefore an important factor in the production of non-ferrous metals. The pyrometallurgical processes are potential sources of dust and metals from furnaces, reactors and the transfer of molten metal.

The main environmental issues associated with the production of non-ferrous metals from secondary raw materials are also related to the off-gases from the various furnaces and transfers that contain dust, metals and in some process steps, acid

gases. There is also the potential for the formation of dioxins due to the presence of small amounts of chlorine in the secondary raw materials; the destruction and/or capture of dioxin and VOCs is an issue that is being pursued.

The main environmental issues for primary aluminum are the production of poly-fluorinated hydrocarbons and fluorides during electrolysis, the production of solid waste from the cells and the production of solid waste during the production of alumina.

The production of solid waste is also an issue for the production of zinc and other metals during the iron removal stages.

Other processes often use hazardous reagents such as HCl, HNO₃, Cl₂ and organic solvents for leaching and purification. Advanced processing techniques are able to contain these materials and recover and re-use them. Reactor sealing is an important issue in this respect.

In the majority of cases these process gases are cleaned in fabric filters and so the emissions of dust and metal compounds such as lead are reduced. Gas cleaning using wet scrubbers and wet electrostatic precipitators is particularly effective for process gases that undergo sulphur recovery in a sulphuric acid plant. In some cases where dust is abrasive or difficult to filter, wet scrubbers are also effective. The use of furnace sealing and enclosed transfers and storage is important in preventing fugitive emissions.

1.4 Energy recovery in the nonferrous industry

Energy and heat recovery is practiced extensively during the production and casting of nonferrous metals. Pyrometallurgical processes are highly heat intensive and the process gases contain a lot of heat energy. As a consequence recuperative burners, heat exchangers and boilers are used to recover this heat. Steam or electricity can be generated for use on or off site and process or fuel gases can be pre-heated. The technique used to recover heat varies from site to site. It is governed by a number of factors such as the potential uses for heat and energy on or near the site, the scale of operation and the potential for gases or their constituents to foul or coat heat exchangers.

2 Zinc

2.1 Zn

Zinc (from German: Zink and also known as spelter) is a metallic chemical element with the symbol Zn and atomic number 30. It is a first-row transition metal in group 12 of the periodic table. Zinc is chemically similar to magnesium because its ion is of similar size and its only common oxidation state is +2. Zinc is the 24th most abundant element in the Earth's crust and has five stable isotopes. The most exploited zinc ore is sphalerite, or zinc sulfide; the largest exploitable deposits are found in Australia, Canada and the United States. Zinc production includes froth flotation of the ore, roasting and final extraction using electricity.

Brass, which is an alloy of copper and zinc, has been used since at least the 10th century BC. Impure zinc metal was not produced in large scale until the 13th century in India, while the metal was unknown to Europe until the end of the 16th century. Alchemists burned zinc in air to form what they called "philosopher's wool" or "white snow." The element was probably named by the alchemist Paracelsus after the German word Zinke. Work by Luigi Galvani and Alessandro Volta uncovered the electrochemical properties of zinc by 1800. Corrosion-resistant zinc plating of steel is the major application for zinc. Other applications are in batteries and alloys, such as brass. A variety of zinc compounds are commonly used, such as zinc chloride (in deodorants), zinc pyrithione (anti-dandruff shampoos), zinc sulfide (in luminescent paints), and zinc methyl or zinc diethyl in the organic laboratory.

Zinc is an essential mineral of "exceptional biologic and public health importance". Zinc deficiency affects about 2 billion people in the developing world and is associated with many diseases. In children it causes growth retardation, delayed sexual maturation, infection susceptibility, and diarrhea, contributing to the death of about 800,000 children worldwide per year. Enzymes with a zinc atom in the reactive center are widespread in biochemistry, such as alcohol dehydrogenase in humans. Consumption of excess zinc can cause ataxia, lethargy and copper deficiency.

2.2 Resources, Production, Usage

About 70% of the world's zinc originates from mining, while the remaining 30% comes from recycling secondary zinc. Commercially pure zinc is known as Special High Grade, often abbreviated SHG, and is 99.995% pure. [

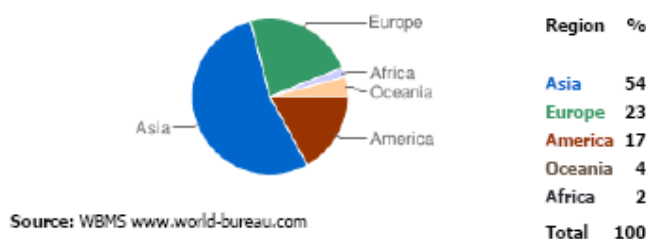
The metal is produced from a range of zinc concentrates by pyrometallurgical or hydrometallurgical processes. Some concentrates contain high proportions of lead and these metals are also recovered. Zinc is also associated with cadmium and the concentrates are a source of this metal.

Secondary raw materials such as galvanising residues (ashes, skimmings, sludges etc), flue dust from steel plants and brass processing and die-casting scrap are also sources of zinc. The recycling of zinc and zinc containing products is a key issue for the industry.

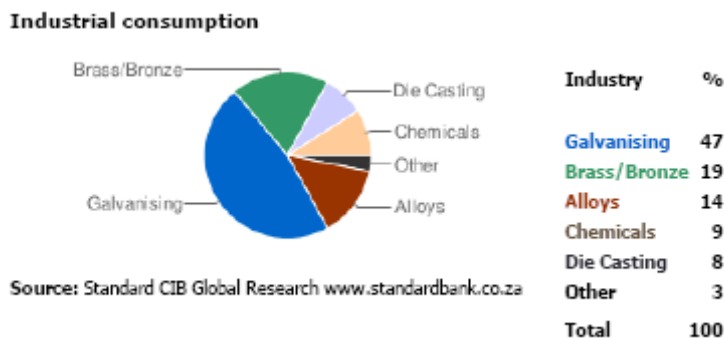
Worldwide, 95% of the mined zinc is from sulfidic ore deposits, in which sphalerite ZnS is nearly always mixed with the sulfides of copper, lead and iron. There are zinc mines throughout the world, with the main mining areas being China, Australia and Peru. China produced over one-fourth of the global zinc output in 2006. [

World production was 11,336,500 tons per annum in 2007.

World zinc production



Zinc has the third highest usage of nonferrous metal, behind aluminum and copper. It has a relatively low melting point and is used in the production of a number of alloys such as brass. It can easily be applied to the surface of other metals such as steel (galvanising) and when it is used as a metal coating, zinc corrodes preferentially as a sacrificial coating. Zinc is also used in the pharmaceutical, nutrient, construction, battery and chemical industries.



Zinc is supplied to the market in various qualities, the highest quality is special high grade (SHG) or Z1 which contains 99.995% zinc while the lowest quality good ordinary brand (GOB) or Z5 is about 98% pure. There are produced extrusion products such as bars, rods, wires (mainly brass), troling products such as sheets and strips and casting alloys and powders and chemical compounds, such as oxides.

Galvanized sheet zinc is substituted by aluminum, plastics, and steel. In the production of diecasting materials, those using aluminum, magnesium, and plastics are major competitors to those using zinc. Aluminum alloy, cadmium, paint, and plastic coatings can substitute for zinc in corrosion protection and aluminum alloys also substitute for brass. A large number of elements can act as substitutes for zinc in chemical, electronic, and pigment uses.

2.3 Processes applied in the zinc industry

Zinc is often associated together with lead and cadmium in ores and concentrates and a number of techniques are used to win and separate these metals. The chemical state (sulphidic or oxidic) and the relative proportion of the metals usually determine the pyrometallurgical or hydrometallurgical technique or combinations that are used. Some of the techniques are also used for secondary or mixed primary and secondary raw materials. In some cases secondary materials are separated and portions such as battery paste are sent to other processors who can deal with that material.

2.3.1 Production of Zinc Concentration

The principal zinc ore mineral is sphalerite, a zinc sulphide, ZnS in pure form of (Zn Fe)S when containing iron. Zinc concentration is usually done at the mine site before sending the concentrate to the processing plant. Concentration is achieved using crushing and grinding followed by froth flotation as is described with copper above.

2.3.2 Primary Zinc Processing

Once concentrated the zinc is reduced using pyrometallurgical methods, including distillation, or hydrometallurgical methods, such as electrowinning, calcination, leaching, or purification. Electrowinning is most commonly used whereby an electrolytic cell is used, as with the process described for copper above, to reduce the zinc. An electric current is run from a lead-silver anode through a zinc solution and the zinc deposits on an aluminum cathode from where it is harvested. The zinc can then be melted and cast into ingots.

The figure below shows the pyrometallurgical route, the second figure below shows the hydrometallurgical route of zinc processing.

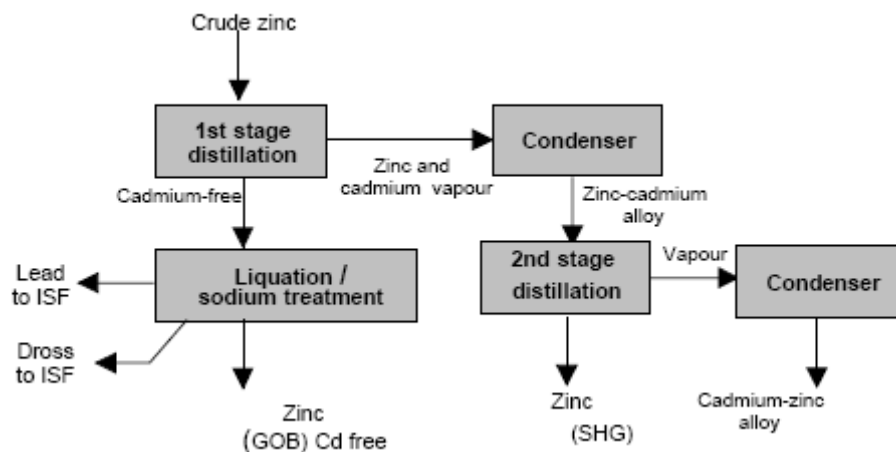


Diagram of zinc/cadmium distillation

The pyrometallurgical route is used for mixed zinc/lead concentrates.

The hydrometallurgical route is used for zinc sulphide (blendes), oxide, carbonate or silicate concentrates and is responsible for about 80% of the total world output.

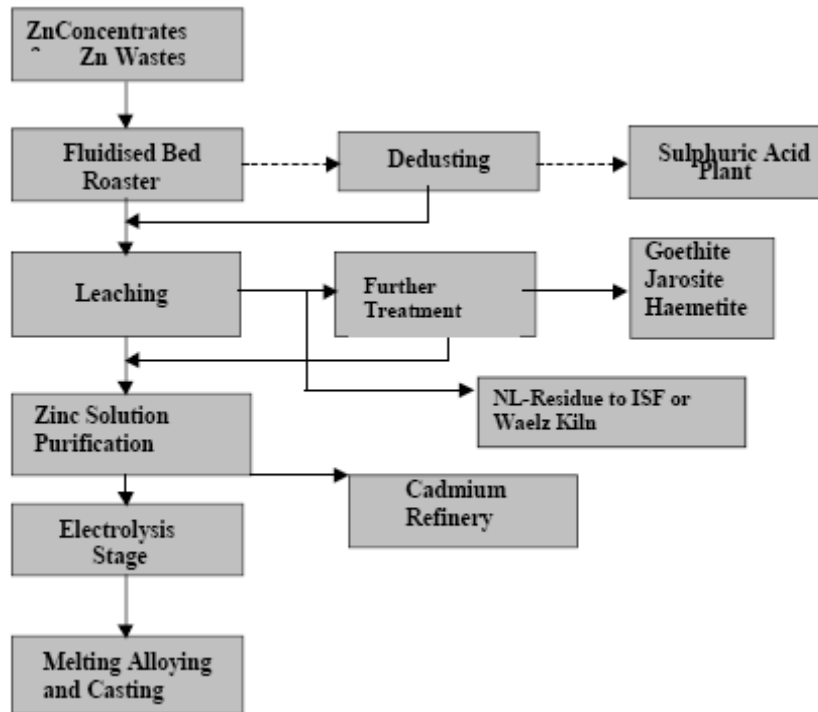


Diagram of the zinc hydrometallurgical process

Through the process of electrolysis zinc is leached from the ore concentrate using sulphuric acid. This process is also known as Roast-Leach Electrowinning (RLE) or SX-EW and comprises the following 4 stages: leaching, purification, electrolysis, and melting and casting.

- Leaching

There are two steps in the double leaching process; the zinc calcine is leached in a neutral or weak sulphuric acid solution. Through this some of the zinc is leached from the zinc oxide. The remaining calcine is leached in strong sulphuric acid to extract as much of the remaining zinc as possible from zinc oxide and zinc ferrite. There will still be impurities in the leach product such as copper, arsenic, antimony and nickel. These are removed in a purification process prior to electrowinning as impurities reduce the efficiency and recovery levels attained through the electrowinning process by

altering the decomposition voltage so that the electrolysis cell produces hydrogen gas as opposed to zinc.

- Purification

In order to remove the impurities, zinc dust is added to large agitated tanks that are heated to between 40 and 85°C and at pressures varying from atmospheric to 2.4atm. Purification reduces the concentration of the impurities to less than 0.05mg/l.

- Electrolysis

Applying the same principles as with electrolysis to extract copper, zinc is extracted from the purified zinc sulphate solution by passing an electric current through the solution in a series of cells causing the zinc to deposit on the cathodes, which comprise aluminium sheets. As with copper, sulphuric acid is produced as a result of the reaction, which can be reused in the leaching step. The zinc loaded aluminium sheets are removed from the cell every 24 to 48 hours, rinsed and the zinc is mechanically stripped.

During electrolysis, heat is generated thereby increasing the temperature; the electrolyte cells usually operated at temperatures ranging from 30 to 35°C and at atmospheric pressure. In order to maintain the stable operating temperatures, the electrolyte is continuously circulated through the cooling towers, which also concentrates the electrolyte as water is evaporated off.

The electrolysis process uses a large amount of electrical energy and accounts for a significant amount of the energy usage in the whole process flowsheet. Electrolysis typically accounts for approximately one third of total plant cash costs and is therefore a crucial target for energy efficiency (Nystar, 2009).

The two common processes for electrowinning are low current density process and the Tainton high current density process. The low current density process uses a 10% sulphuric acid solution with current density of 270-325 amperes per square metre. The high current density process uses 22-28% sulphuric acid as the electrolyte with a current density of approximately 1000 amperes per metre squared resulting in higher purity zinc and a greater production capacity per volume of electrolyte. However, the

system runs at higher temperatures and can be more corrosive to the cells. In both processes, production of a metric ton of zinc, requires approximately 3,900kWh (14GJ) of electrical power.

2.3.3 Secondary Zinc Processing

Secondary zinc production accounts for approximately 30% of the world's zinc production and uses process scrap from zinc slabs, zinc oxides and zinc dust. Approximately 50% of this secondary zinc is recycled within the consumers or users industry. This is particularly true in the galvanising and brass sector; scrap arising from the production or processing of products can be recycled almost immediately. Selective melting may also be used to capture zinc if the zinc is mixed with other non-ferrous metals with higher melting points. Zinc can also be recovered from the furnace dust of galvanized steel making plants. Once captured, secondary zinc first undergoes a separation process using magnetic separation, sink-float or hand sorting are usually used to remove the zinc from unwanted components. After separation, the zinc is melted in a kettle, crucible, reverberatory furnace or electric induction furnace, with new scrap from brass plants, rolling zinc clippings or die casting. Flux is used to remove impurities and produces dross (distinguished from slag as it is solid as opposed to liquid) that is skimmed from the surface of the molten zinc; the zinc is then either poured into molds or sent to refiners. High quality scrap from dross, diecastings, and other zinc rich sources usually can be remelted without further refinement.

The process route used to recover zinc depends on the form and concentration of zinc, and the degree of contamination. Process details are very often confidential.

Two specific process types of secondary zinc production are:

- Waelz kilns

The process is designed to separate zinc (and lead) from other materials by reducing, volatilising and oxidising zinc (and lead) again.

- Slag fuming processes

These processes are also used to recover zinc from residues. Electric arc furnace dust, most of the slags from lead smelting operations and other residues from zinc reduction contain lead and zinc that will be lost if they are

not treated further. These materials may be fumed with a source of carbon such as coal, to recover lead and zinc and to raise heat from the process.

2.3.4 Melting and alloying processes for zinc

Melting and alloying are usually carried out in indirectly fired crucible furnaces or induction furnaces; temperature control is practiced to ensure that zinc is not volatilised forming fume. The fuel is usually either gas or oil. The gas or oil burner can be located outside the crucible, which is encased in a combustion box, or inside the crucible as an immersion tube heater. In both cases, temperature control is critical, as the casting temperature must not exceed 450 °C for most alloy compositions to avoid metal loss by fuming.

2.3.5 Casting processes for zinc

Zinc is melted in electric furnaces and temperature control is practiced to prevent fuming. The zinc bath is periodically skimmed to remove solids ('dross': zinc oxide and zinc chloride). A flux is often added to reduce the loss of zinc in the 'dross'. The dross can be recycled within the ISF or to the roaster in the electrolytic zinc process. Metal is usually cast into permanent moulds that are commonly made of cast iron. Stationary or continuous conveyor casting machines are used. Static moulds and conveyor casting machines are used to produce blocks and ingots. Continuous casting machines are used to produce rod for reduction to wire.

2.3.6 Production of zinc dust

Zinc dust is produced as a product for other industrial processes and as reagent for use during the leach liquor purification route. Molten zinc produced by the same techniques outlined above is sprayed under pressure through an atomising nozzle and is then rapidly cooled in an inert atmosphere to produce dust. Air, water or centrifugal atomisation of a stream of molten zinc can also be used to produce dust.

The dust is removed in bag filter system and conveyed to the process or packaged.

2.3.7 Cadmium

Cadmium is produced as a by-product from many of the metal recovery processes. The production of zinc and lead are the main sources.

2.4 Energy

2.4.1 Energy use

The energy requirement for the different zinc processes varies to a large extent. It depends on the quality of the feed and the products, the use of latent or waste heat and the production of by-products. The energy efficiency of zinc production and processing will be heavily dependent upon the nature of the original ore or raw materials.

2.4.2 Energy benchmarks

The following table shows the average energy requirements of the different processes.

Process	Energy related to: -	Electrical kW/h per t	Coke kg/t	Natural gas Nm ³ /t
Zinc electrolysis	t zinc	4100		
ISF & NJ distillation	t zinc	1050	1100	220
	t Metal	750	785	160
Waelz kiln	t WO leached	200	850	20
Slag fuming	t slag	150	250	

2.4.3 Energy recovery

The following examples are typical and constitute techniques to consider for use in the processes to produce non-ferrous metals. The techniques described can be incorporated into many existing processes:

- The hot gases produced during the smelting or roasting of sulphide ores are almost always passed through steam raising boilers. The steam produced can be used to produce electricity and/or for heating requirements. An example of this is where a copper smelter produces 25% of its electrical requirements (10.5 MVA) from the steam produced by the waste heat boiler of a flash furnace. In addition to electricity generation, steam is used as process steam, in the concentrate dryer and residual waste heat is used to pre-heat the combustion air.
- Other pyrometallurgical processes are also strongly exothermic, particularly when oxygen enrichment of combustion air is used. Many processes use the excess heat that is produced during the smelting or conversion stages to melt secondary materials without the use of additional fuel. For example the heat given off in the Pierce-Smith converter is used to melt anode scrap. In this case the scrap material is used for process cooling and the additions are carefully controlled, this avoids the need for cooling the converter by other means at various times of the cycle. Many other converters can use scrap additions for cooling and those that are not able are subject to process developments to allow it.
- The use of oxygen enriched air or oxygen in the burners reduces energy consumption by allowing autogenic smelting or the complete combustion of carbonaceous material. Waste gas volumes are significantly reduced allowing smaller fans etc to be used.
- Furnace lining material can also influence the energy balance of a melting operation. In this case Low Mass refractories are reported to have a beneficial effect by reducing the thermal conductivity and storage in an installation. This factor must be balanced with the durability of the furnace lining and metal infiltration into the lining and may not be applicable in all cases.
- Separate drying of concentrates at low temperatures reduces the energy requirements. This is due to the energy required to super heat the steam within a smelter and the significant increase in the overall gas volume, which

increases fan size.

- The production of sulphuric acid from the sulphur dioxide emitted from roasting and smelting stages is an exothermic process and involves a number of gas cooling stages. The heat generated in the gases during conversion and the heat contained in the acid produced can be used to generate steam and /or hot water.
- Heat is recovered by using the hot gases from melting stages to pre-heat the furnace charge. In a similar way the fuel gas and combustion air can be pre-heated or a recuperative burner used in the furnace. Thermal efficiency is improved in these cases. For example, nearly all cathode/copper scrap melting shaft furnaces are natural gas fired, the design offers an thermal efficiency (fuel utilisation) of 58% to 60%, depending on diameter and height of the furnace. Gas consumption is approximately 330 kWh/tonne of metal. The efficiency of a shaft furnace is high, principally because of charge preheating within the furnace. There can be sufficient residual heat in the off-gas to be recovered and re-used to heat combustion air and gas. The heat recovery arrangement requires the diversion of the furnace stack gases through a suitably sized heat exchanger, transfer fan and ductwork. The heat recovered is approximately 4% to 6% of the furnace fuel consumption.
- Cooling prior to a bag filter installation is an important technique as it provides temperature protection for the filter and allows a wider choice of fabric. It is sometimes possible to recover heat at this stage. For example in a typical arrangement used by a shaft furnace to melt metal, gases from the top of the furnace are ducted to the first of two heat exchangers that produces preheated furnace combustion air. The temperature of the gases after this heat exchanger can be between 200 and 450 °C. The second heat exchanger reduces the gas temperature to 130 °C before the bag filter. The heat exchangers are normally followed by a cyclone, which removes larger particles and acts as a spark arrester.
- Carbon monoxide produced in an electric or blast furnace is collected and burnt as a fuel for several different processes or to produce steam or other energy. Significant quantities of the gas can be produced and examples exist where a major proportion of the energy used by an installation is produced from the CO collected from an electric arc furnace installation. In other cases the CO formed in an electric furnace burns in the furnace and provides part of

the heat required for the melting process.

- The re-circulation of contaminated waste gas back through an oxy-fuel burner has resulted in significant energy savings. The burner recovers the waste heat in the gas, uses the energy content of the contaminants and removes them. Such a process can also reduce nitrogen oxides.
- The use of the heat content of process gases or steam to raise the temperature of leaching liquors is practiced frequently. In some cases a portion of the gas flow can be diverted to a scrubber to recover heat into the water, which is then used for leaching purposes. The cooled gas is then returned to the main flow for further abatement.
- During the smelting of electronic scrap or battery scrap in metallurgical vessels the heat content of the plastic content is used to melt the metal content and other additional scrap and slag forming components.

The advantage of preheating the combustion air used in burners is well documented. If an air preheat of 400 °C is used there is an increase in flame temperature of 200 °C, while if the preheat is 500 °C the flame temperature increases by 300 °C. This increase in flame temperature results in a higher melting efficiency and a reduction in energy consumption.

The alternative to preheating the combustion air is to preheat the material charged to the furnace. Theory shows that 8% energy savings can be obtained for every 100 °C preheat and in practice it is claimed that preheating to 400 °C leads to 25% energy savings while a preheat of 500 °C leads to a 30% energy savings. Pre-heating is practiced in a variety processes.

Heat and energy recovery is therefore an important factor in this industry and reflects the high proportion of costs that energy represents. Many techniques for energy recovery are relatively easy to retrofit but there are occasionally some problems of deposition of metal compounds in heat exchangers. Good design is based on a sound knowledge of the compounds released and their behaviour at various temperatures. Heat exchanger cleaning mechanisms are also used to maintain thermal efficiency.

Whilst these savings are examples of individual components of installations they are critically dependant upon the site and process specific conditions including economics.

3 Gold

3.1 Precious Metals

Gold is a nonferrous metal and belongs to the exclusive group of precious metals in good company with other such well-known metals as silver and the six platinum group metals: platinum, palladium, rhodium, iridium, ruthenium and osmium. They are termed precious metals because of their rarity and corrosion resistance.

The EU has the largest refining and fabricating capacity for precious metals in the world, even though its actual mineral resources of such metals are very limited. The recycling of precious metals from scrap and industrial residues has always been an important raw material source for the industry.

Consumption of gold is mainly for jewelry, with smaller amounts used in electronics and other industrial and decorative applications. The principal users of silver are the photographic and jewellery industries. The platinum group metals are used extensively as catalysts and the imposition of strict emissions limits on vehicles has stimulated demand for their use in catalytic converters.

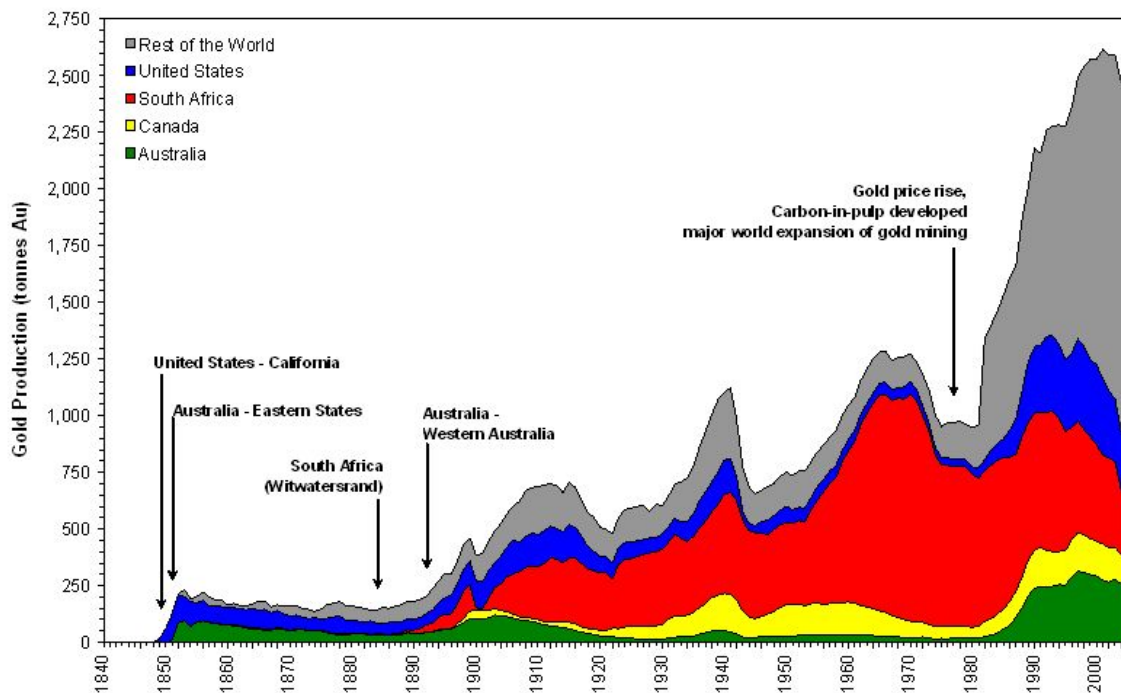
3.2 Au (aurum)

Gold is a chemical element with the symbol Au (Latin: aurum) and an atomic number of 79. It has been a highly sought-after precious metal in jewelry, in sculpture, and for ornamentation since the beginning of recorded history. The metal occurs as nuggets or grains in rocks, in veins and in alluvial deposits. Gold is dense, soft, shiny and the most malleable and ductile pure metal known. Pure gold has a bright yellow color and luster traditionally considered attractive, which it maintains without oxidizing in air or water. It is one of the coinage metals and formed the basis for the gold standard used before the collapse of the Bretton Woods system in 1971.

3.3 Gold Resources, Production and Consumption

It was estimated that all the gold ever mined until the year 2006 totaled 158,000 tonnes. This can be represented by a cube with an edge length of just 20.2 meters. In 2007 the annual world production of gold was 2,380 metric tons (32,150.7 troy ounces).

The figure below shows the historical trend in gold production over the last 150 years.

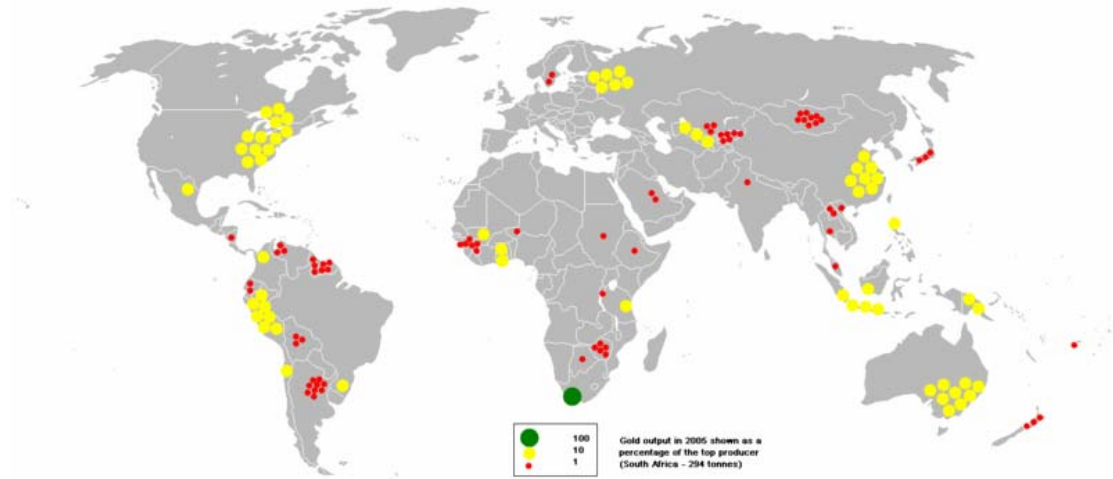


Historical Trend in Gold Production

Since the 1880s, South Africa has been the source for a large proportion of the world's gold supply, with about 50% of all gold ever produced having come from South Africa. Production in 1970 accounted for 79% of the world supply, producing about 1,000 tons. However by 2007 production was just 272 tonnes. This sharp decline was due to the increasing difficulty of extraction, changing economic factors affecting the industry, and tightened safety auditing. In 2007 China (with 276 tonnes) overtook South Africa as the world's largest gold producer, the first time since 1905 that South Africa has not been the largest.

Other major producers are the United States, Australia, Russia and Peru.

The bubble map below shows the global distribution of mined output of gold in 2005 as a percentage of the top producer South Africa.



Gold extraction is most economical in large, easily mined deposits. Ore grades as little as 0.5 g/1000kg (0.5 parts per million, ppm) can be economical. Typical ore grades in open-pit mines are 1–5g/1000kg (1–5ppm); ore grades in underground or hard rock mines are usually at least 3 g/1000kg (3 ppm). Because ore grades of 30 g/1000kg (30 ppm) are usually needed before gold is visible to the naked eye, in most gold mines the gold is invisible.

Despite the general increase in resources of gold year on year, as new deposits are discovered and investigated, there has been a general trend in reducing gold ore grades.

India is the world's largest consumer of gold. Indian consumers buy about 25 per cent of the world's gold. Indians buy approximately 800 tonnes of gold every year. India is also the largest importer of the yellow metal; in 2008 India imported around 400 tonnes of gold.

Gold in particular is usually turned into specific alloys for jewellery or dental purposes in order to improve its wear-resistance or colour. Because of the high intrinsic value and the wide range of forms and alloys required, such metals are usually fabricated or processed in relatively small quantities compared with base metals.

3.4 Gold processing

A variety of processes have been developed which exploit the chemical properties of precious metals. Although they are relatively inert, their reactivity varies and the various oxidation states of the metal in their compounds allow a variety of separation techniques to be used. Many of the processes use very reactive reagents or produce toxic products, these factors are taken into account by the use of containment, fail safe systems and sealed drainage areas. This is further driven by the high value of the metals.

Many of the process are commercially confidential and outline descriptions only, are available. The processes are usually carried in various combinations to recover the precious metals that are present in a particular feedstock. The other feature of the industry is that generally, the precious metals are recovered on a toll basis, which can be independent of the metal value. Much of the processing is therefore designed to accurately sample and assay the material as well as recover it. Sampling is carried out after the material has been processed physically or from side streams during normal processing. There are hundred types of raw materials available to the industry and they are normally characterised into five homogenisation types.

Homogenisation category	Type of raw material	Comment
Original	Catalysts, Prepared Sweeps, Solutions.	Direct to process
Sweeps	Mineral + metal, non-fusible carbon catalysts.	Incineration, roasting and pre-enrichment
Scrap	Fusible material.	
Material to be shredded	Film, electronic scrap.	
Materials for dissolution	Material that is dissolved in acid, CN, NaOH etc.	

Historically, native gold (free gold) has been processed through gravity concentration using pans on a small scale or washing tables; this process is still commonly used in artisanal and small scale mining. Where gold is present in the ore as discrete coarse particles a gravity concentrate can be directly smelted to form gold bullion. Where gold is present in the ore as very fine particles or when it is not sufficiently liberated from the host rock following crushing and grinding, a process of cyanidation is used whereby the concentrates are treated with cyanide salts to leach the gold, which is

then recovered from the pregnant leach solution by adsorption on activated carbon followed by solution concentration or stripping and/or electrowinning.

Gold can also be present as a by-product, for example in base metal deposits, in which case it can be recovered during the processing of the primary product. For example, in base metal processing it can be recovered in the anode slime during the electrorefining.

3.4.1 The Miller process

The Miller process can be used to pre-treat the material. In this process the feed materials are melted in an indirectly heated crucible or electric induction furnace while chlorine gas is injected into the melt. At the operating temperature of about 1000°C, gold is the only metal present that does not react to form a stable molten or volatile chloride. Molten silver chloride rises to the surface of the melt. A borax flux is used to assist collection and skimming of the metal chlorides. Zinc in the feed is converted to zinc chloride which, together with volatile metal chlorides, is exhausted to a gas scrubbing system. The Miller process is operated to produce either 98% gold, which is cast into anodes for electrorefining, or 99.5% gold that is cast into bullion bar.

3.4.2 Electro-refining

Gold anodes are refined in Wohlwill cells containing gold foil or titanium cathodes. The electrolyte used is an acidic gold chloride solution maintained at about 70 °C. An electric current applied between the electrodes causes gold ions dissolved from the anodes to migrate and deposit on the cathodes yielding a product containing 99.99% gold.

3.4.3 Leaching with Aqueous Cyanide Solutions

The gold-cyanide complex, formed by leaching gold in an aqueous cyanide solution

is very stable and, in theory, the cyanide required is only slightly in excess of the stoichiometric requirement. In practice, the amount of cyanide used in leach solutions is dictated by the presence of other cyanide consumers, such as organic carbon, and the level required to achieve an economic rate of leaching. Typical cyanide concentrations used in practice range from 300 to 500 mg/l (0.03 to 0.05% as NaCN) depending on the mineralogy of the ore.

The gold is recovered by either heap leaching or agitated pulp leaching. With heap leaching the ore or agglomerated fine ore is stacked on a leach pad lined with an impermeable membrane. Cyanide solution is introduced to the heap by sprinklers or a drip irrigation system; the solution percolates through the heap leaching the gold from the ore and the resultant 'pregnant' gold-bearing solution is collected on the impermeable membrane and channeled to storage facilities for further processing. Heap leaching is attractive due to the low capital cost required but it is a slow process and the gold recovery is relatively low at 50-75%.

In a conventional milling and agitated leaching circuit, the ore is crushed and ground to powder in semi-autogenous ball or rod mills. The milled ore, also known as slurry is transferred, commonly by conveyor, to a series of leach tanks. The slurry is agitated in the leach tanks, either mechanically or through air injection, in order to increase the contact of cyanide and oxygen with the gold thereby improving the efficiency of the leach process. The use of oxygen or peroxygen compounds instead of air as an oxidant increases the leach rate and decreases cyanide consumption, due to the inactivation of some of the cyanide consuming species present in the slurry. The pH of the slurry is raised to pH 10-11 using lime, at the head of the leach circuit to ensure that when cyanide is added, toxic hydrogen cyanide gas is not generated and the cyanide is kept in solution to dissolve the gold. The slurry may also be subject to other preconditioning such as pre-oxidation at the head of the circuit before cyanide is added.

Highly activated carbon is used in the dissolved gold recovery process, either by introducing it directly into the CIL (carbon-in-leach) tanks or into separate CIP (carbon-in-pulp) tanks after leaching. The activated carbon adsorbs the dissolved gold from the leach slurry or agitated pulp thereby concentrating it onto a smaller mass of solids.

When carbon is not used to adsorb the dissolved gold, the gold bearing solution must be separated from the solids components using filtration or thickening units. The resultant solution, referred to as pregnant solution, is subjected to further treatment

(other than by carbon absorption) to recover the dissolved gold.

The waste from which the gold was removed by any means is referred to as residue or tailings material. The residue is either dewatered to recover the solution, treated to neutralise or recover cyanide, or is sent directly to the tailing management facility.

3.4.4 Recovery of Dissolved Gold

The traditional Merrill Crowe method has been the preferred separation technique for removing gold from a pregnant cyanide solution. The solution is separated from the ore through filtration and counter current decantation (CCD), which prevents 'blinding' by near sized carbon particles, thereby filtering the gold out of the solution. The pulp residue can then be thickened to separate the solution containing cyanide to recover or destroy the cyanide or it is sent to the tailing management facility (TMF) from where the cyanide solution can be recycled to the leach plant for reuse. The gold solution is then clarified in filters commonly coated with diatomaceous earth, a soft, chalk-like sedimentary deposit that contains fossils of diatoms (a hard shelled algae), to produce a clarified solution. Oxygen is removed by passing the clarified solution through a vacuum de-aeration column. Zinc dust is added resulting in precipitation of the gold as zinc has a greater affinity for the cyanide ion; other metals such as copper and silver also precipitate at this stage should they be present. Activated carbon in contact with a pulp containing gold can typically recover more than 99.5% of the gold in the solution in 8 to 24 hours, depending on the reactivity of the carbon, the amount of carbon used and the efficiency of the system.

3.4.5 Refractory gold processes

A "refractory" gold ore is an ore that is naturally resistant to recovery by standard cyanidation and carbon adsorption processes. These refractory ores require pre-treatment in order for cyanidation to be effective in recovery of the gold. A refractory ore generally contains sulfide minerals, organic carbon, or both. Sulfide minerals often trap or occlude gold particles, making it difficult for the leach solution to complex with the gold. Organic carbon present in gold ore may adsorb dissolved gold-cyanide complexes in much the same way as activated carbon. This so-called

"preg-robbing" carbon is washed away because it is significantly finer than the carbon recovery screens typically used to recover activated carbon.

Pre-treatment options for refractory ores include:

- Roasting
- Bio-oxidation
- Pressure oxidation
- Ultrafine grinding

The refractory ore treatment processes may be preceded by concentration (usually sulfide flotation). Roasting is used to oxidize both the sulfur and organic carbon at high temperatures using air and/or oxygen. Bio-oxidation involves the use of bacteria that promote oxidation reactions in an aqueous environment. Pressure oxidation is an aqueous process for sulfur removal carried out in a continuous autoclave, operating at high pressures and somewhat elevated temperatures. Ultrafine grinding may be used when liberation of gold particles from the surrounding mineral matrix is the primary refractory characteristic of the ore.

3.5 Emissions and Consumptions

Gold refineries are complex networks of main and subsidiary processes. The raw materials used vary greatly in quality and quantity and therefore the equipment used has a variety of capacities and uses. Multi-purpose reactors and furnaces are used extensively and processing steps are often repeated. It is therefore not possible to identify single process steps and their contribution to emissions and consumption.

Some general principles apply to the emissions and consumption of this sector: -

- On average a 100-fold quantity of material has to be treated to isolate gold. The concentrations vary from < 1% to nearly pure metal.
- High-energy techniques are used e.g. electric furnaces. Energy recovery is practiced if appropriate.
- Residues containing base metals are sold for recovery.
- Many chemical treatments involve the use of cyanide, chlorine, hydrochloric

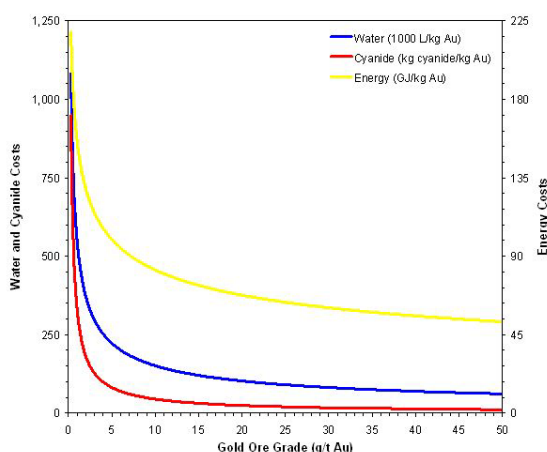
acid and nitric acid. These reagents are reused within the processes but eventually require oxidation or neutralisation with caustic soda and lime. Sludges from wastewater treatment are closely monitored for metals and are recovered if possible.

- A variety of organic solvents are used for liquid-liquid extraction.
- A variety of oxidising and reducing agents are used.
- Acid gases such as chlorine or nitrogen oxides are recovered for reuse.
- Gas volumes vary greatly between cycles. The small scale of the processes usually allows for good containment. Local exhaust ventilation is used.

3.5.1 Energy use and Benchmarks

The energy efficiency of gold production and processing will be heavily dependent upon the nature of the original ore. The energy input to the initial mining of the ore (including excavation, load-haul-dump and crushing and grinding will be least for alluvial gold deposits, where drilling and blasting are not required. Energy requirements will increase with mining from open pit operations and be greatest from deep underground hard rock mines. Notwithstanding this, opportunities for applying energy efficiency to any of these operations are possible.

Despite there being differences in mining costs and processing methodologies, the economics of gold production require that costs of mining and processing must meet economic realities of supply and demand. For this reason there has been found to be a close inverse relationship between production costs and gold ore grade. Since most of the production costs are energy dominated, then these can also be related to energy input.



The figure shows the relationship between energy, water demand and cyanide demand with ore grade.

3.5.2 Energy efficiency options

More specific energy efficiency in the case of gold will mainly relate to the method of processing, with different options being available to each. These are summarised below.

Processing Method	Issues	Comments
Gravity Concentration		<ul style="list-style-type: none"> • Small scale processing of free gold using pans and washing tables; • Direct smelting into bullion.
	Future Options	<ul style="list-style-type: none"> • Already very efficient in terms of energy usage but limited by volume of production and reducing reserves.
Cyanidation	Most common processing method	<ul style="list-style-type: none"> • Used in ores containing very fine grained gold particles; • Cyanide is used to leach gold from the host rocks; • Gold is recovered by adsorption on activated carbon; • This is followed by electro-winning or solution concentration
	Issues	<ul style="list-style-type: none"> • Environmentally hazardous due to the toxicity of cyanide • Requires substantial amounts of cyanide to generate leaching along with sodium hypochloride for cyanide neutralisation
	Future Options	<ul style="list-style-type: none"> • Cyanide recovery and recycling • Tailings washing • High density thickening
Refractory Gold		<ul style="list-style-type: none"> • Refractory gold deposits have an association with sulphides including pyrite and arsenopyrite; • Pre-treatment required by floatation to concentrate and remove sulphides
	Future Options	<ul style="list-style-type: none"> • Bio-oxidation – removal of sulphides using sulphate digesting bacteria • Electrolytic oxidation
Gold with organic carbon		<ul style="list-style-type: none"> • Pre-treatment needed
	Future Options	<ul style="list-style-type: none"> • Electrolytic oxidation

4 References and Links

BEST AVAILABLE TECHNIQUES IN THE NON FERROUS METALS INDUSTRY,
CEMBUREAU 2001 - <http://www.epa.ie/downloads/advice/brefs/Polymers.pdf>

More information can be found by searching in the internet.