

COPPER

Text taken from (Ullmann's Encyclopedia of Industrial Chemistry, 2001)

Copper production

About 80 % of primary *copper* production comes from low-grade or poor sulfide ores. After enrichment steps, the *copper* concentrates are usually treated by pyrometallurgical methods. Generally, *copper* extraction follows the sequence (see Figure below):

1. Beneficiation by froth flotation of ore to give *copper* concentrate
(Optional partial roasting to obtain oxidized material or calcines)
2. Two-stage pyrometallurgical extraction
 1. smelting concentrates to matte
 2. converting matte by oxidation to crude (converter or blister) *copper*
3. Refining the crude *copper*, usually in two steps
 1. pyrometallurgically to fire-refined *copper*
 2. electrolytically to high-purity electrolytic *copper*

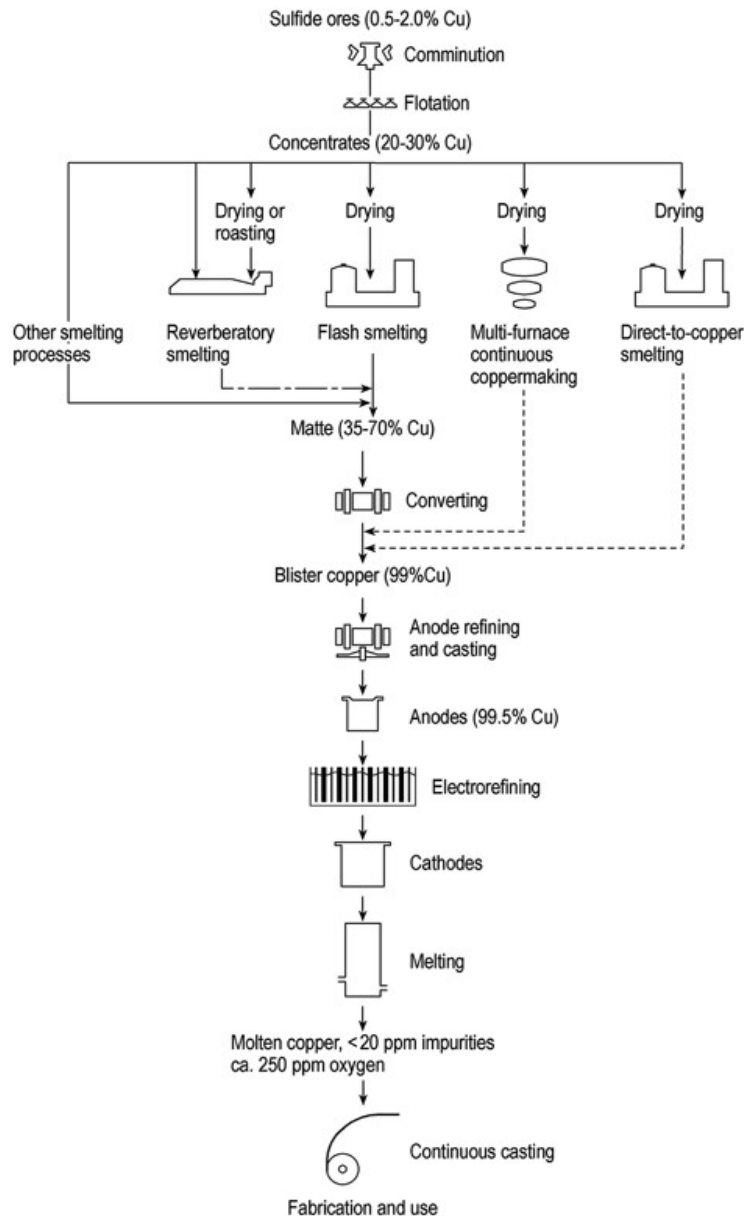


Figure 1: Overview of copper production

Beneficiation process

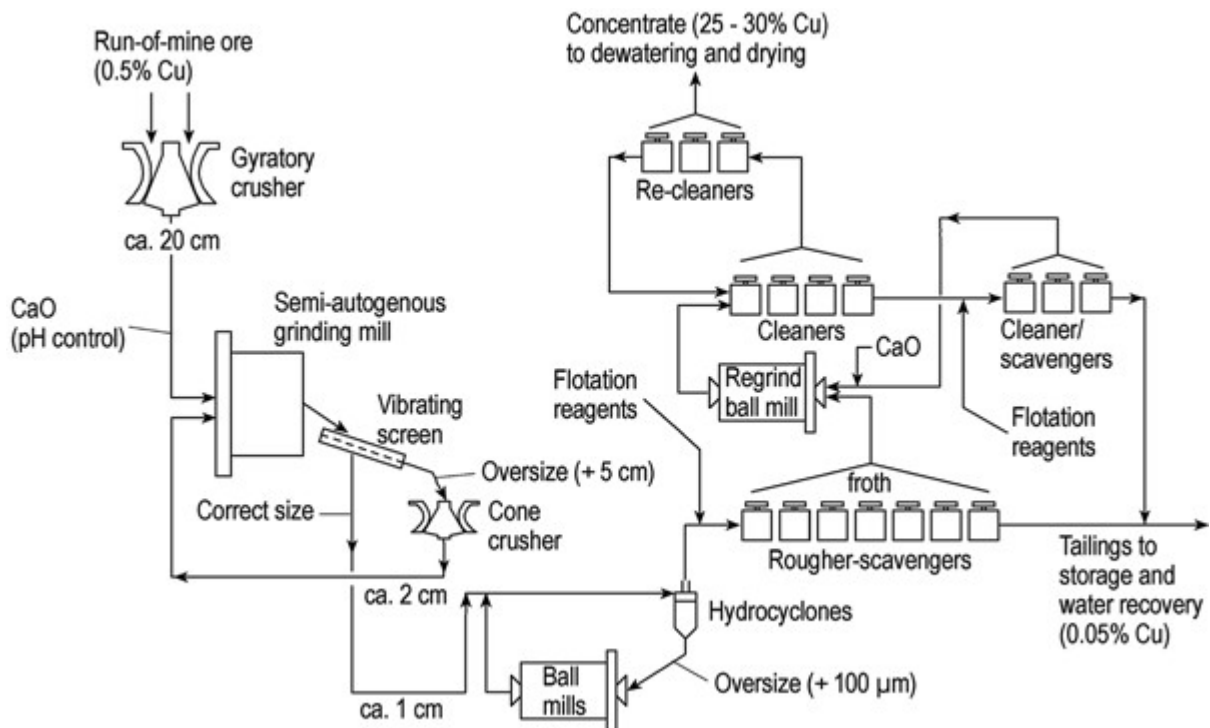


Figure 2: Overview of a typical beneficiation process at a concentrator

Sulfidic *copper* ores are too dilute for direct smelting. Smelting these materials would require too much energy and very large furnace capacities. The *copper* ore coming from the mine (0.5 – 1 % Cu) must be concentrated by beneficiation. The valuable minerals like chalcopyrite are intergrown with gangue. Therefore, in the first step the lumpy ore is crushed and milled into fine particles (< 100 μm) to liberate the individual mineral phases.

Typical equipment for crushing to about 20 cm are gyratory and cone crushers. Then wet grinding in semi-autogenous rod or autogenous ball mills takes place. Size classification takes is performed in cyclones. In the next step of beneficiation, valuable minerals and gangue are separated by froth flotation of the ore pulp, which exploits the different surface properties of the sulfidic *copper* ore and the gangue [46]. The hydrophobic sulfide particles become attached to the air bubbles, which are stirred into the pulp, rise with them to the surface of the pulp, and are skimmed off as a froth of fine concentrate. The hydrophilic gangue minerals remain in the pulp. Organic reagents with sulfur-containing groups at their polar end, such as xanthates, are used as collectors in the flotation process. Additionally, modifiers like hydroxyl ions (pH adjustment) are used to select different sulfide minerals, for example, chalcopyrite and pyrite. Alcohols are used to stabilize the froth.

To obtain concentrates with highest possible purity and recovery rate, the flotation process usually consists of several stages which are controlled by expert systems. Various sensors for particle size, pH, density, and other properties are installed. Figure 4 gives an overview of a typical beneficiation process at a concentrator. In the first flotation stage, as much *copper* as possible is recovered in a rougher concentrate so that as little as possible goes to the tailings. To increase the *copper* recovery rate, often these tailings are leached with sulfuric acid. After regrinding, the rough concentrate is

cleaned in several flotation steps. After sedimentation in thickeners and filtration in automatic filter presses or vacuum filters (ceramic disk) the typical *copper* concentrate contains 25 – 35 % Cu and about 8 % moisture. The moisture content of the concentrate is a compromise between transporting water (cost) and avoiding dust generation during transport. Dewatered concentrates may heat spontaneously or even catch fire; therefore, appropriate precautions must be taken [47].

Copper concentrators typically treat up to 100 000 t of ore per day. They are located directly at the mines to achieve low transport costs. The *copper* recovery efficiency is over 90 %. About 95 % of the ore input goes into the tailings, which are stored in large dams near the mine and are used for water recycling to the flotation stages.

Separation of special *copper* ores such as those containing molybdenite or with high zinc or lead content (Canada) is also possible by flotation methods. Flotation of non-sulfide *copper* minerals is rare because these ores are mostly subjected to hydrometallurgical *copper* recovery, for example, heap leaching. In Zambia and Zaire, however, siliceous *copper* oxide ores are floated with fatty acid collectors, and dolomitic *copper* oxide ores are sulfidized with sodium hydrosulfide and then floated [48].

Pyrometallurgical copper production

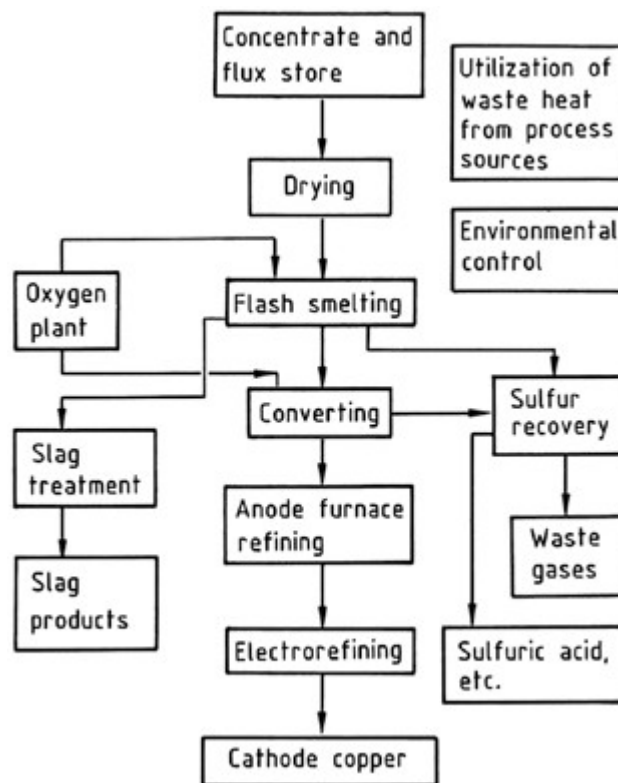


Figure 3: Typical flow sheet for pyrometallurgical copper production from ore concentrates

The large blast and reverberatory furnaces of the 1900s were derived from these principles. Later, the electric furnace for matte smelting was developed. Newer processes are the Isasmelt/Ausmelt/Csiromelt (furnace with vertical blowing lance), the Noranda and CMT/Teniente reactors (developed from converters), the Russian Vanyukov, and the Chinese Bayia process.

5.4.1. Blast Furnace Smelting

The blast or shaft furnace is well-suited for smelting high-grade, lumpy *copper* ore. If only fine

concentrates are available, they must first be agglomerated by briquetting, pelletizing, or sintering. Because of this additional step and its overall low efficiency, the blast furnace lost its importance for primary *copper* production and is currently used in only a few places, for example, Glogow in Poland.

Smaller types of blast furnace, however, are used to process such copper-containing materials as intermediate products (e.g., cement *copper* or copper(I) oxide precipitates), reverts (e.g., converter slag, refining slag, or flue dusts), and copper-alloy scrap.

The construction of the furnace is basically related to that of the iron blast furnace, but there are considerable differences in design, especially in size and shape: the *copper* blast furnace is lower and smaller, and its cross section is rectangular. Developments adopted from the steel industry include use of preheated air (hot blast), oxygen-enriched air, and injection of liquid fuels.

The furnace is charged with alternate additions of mixture (copper-containing materials and accessory fluxes such as silica, limestone, and dolomite) and coke (which serves as both fuel and reducing agent). There are three zones in the furnace:

1. In the heating zone (the uppermost), water evaporates and less stable substances dissociate.
2. In the reduction zone, heterogeneous reactions between gases and the solid charge take place.
3. In the smelting zone, liquid phases react.

The usual mode of operation is reducing smelting, which yields two main products. Sulfide ores are used to produce a matte (40 – 50 wt % Cu) and a disposal slag (ca. 0.5 wt % Cu). In contrast, oxide ores are processed directly to impure black *copper* ($\cong 95$ wt % Cu) and to a copper-rich slag. The two ore types can be smelted together to produce matte and a slag with low *copper* content. Another product is top gas, which contains flue dust. Ores that contain high concentrations of arsenic and antimony also form speiss, which is difficult to decompose.

In Poland (KGHM Polska Meidz S.A. Smelters in Glogow I and Legnica) the blast-furnace technology is well adapted to Polish *copper* concentrates, which contain about 20 – 30 % Cu like normal chalcopyrites but also 5 – 10 % of organic carbon and only 9 – 12 % S. Also these concentrates have relatively high lead (up to 2.5 %) and arsenic (up to 0.3 %) content. The organic carbon compounds provide about 40 – 60 % of the process energy; the rest is added by coke. The matte has about 58 – 63 % Cu and 3 – 6 % Pb. The slag contains less than 0.5 % Cu. The off-gas from the blast furnaces (three in each plant) is mixed with the converter gases (Hoboken Converter). It contains 7 – 10 % SO₂ and is sent to sulfuric acid production. The production figures are 80 000 t/a converter *copper* in Legnica, and 200 000 t/a in Glogow I Smelter [214].

5.4.2. Reverberatory Furnace Smelting

The reverberatory furnace dominated *copper* matte smelting for much of the 1900s, because it was an excellent process for smelting fine concentrate from flotation. It is a fossil fuel fired hearth furnace for smelting concentrate and producing *copper* matte. The reverbs began to decline in the 1970s with the adoption of environmentally and energetically superior processes like flash smelting. Probably the last one was erected in 1976 in Sar Chemesh, Iran. In 1980 about 100 reverbs were in operation, but in 1994 the number had decreased to about 25. As shown in Figure 10 it is a rectangular furnace up to 10 m wide and 35 m long with internal brick lining. Throughputs of up to 1100 t/d concentrate or a mixture of concentrate and calcine could be processed. The charge is passed into the furnace near the burners through the roof or lateral openings. As fossil fuel, pulverized coal, heavy oil, or natural gas is used. Normally the burner is located in the front wall of the furnace. The atmosphere is slightly oxidizing, and the maximum flame temperature is up to 1500 °C. During the 1980s oxygen – fuel burners have been set in the roof to fire downwards

directly on the top of the bath. This increases the smelting rate by up to 40 % and the energy efficiency to about 50 % [76], [215]. Another invention was the sprinkler burner for feeding concentrate, coal, and flux from the top of the reverb [77].

Autogenous Smelting

Autogenous smelting involves the use of combustion heat generated by reactions of the feed in an oxidizing atmosphere in which the sulfide concentrate acts partly as a fuel. The formerly separate steps of roasting and smelting are combined into a roast – smelting process. The spatial and temporal coupling of exothermic and endothermic reactions leads to an economical process, but the sensible heat of nitrogen in the air causes a deficit in the heat balance. In practice, various measures must be taken:

1. Increasing the oxygen content of the combustion air and even using pure oxygen
2. Preheating combustion air with waste heat or in a preheater
3. Combustion of natural gas, fuel oil, or pulverized coal in supplementary burners

To achieve autogenous operation and prevent agglomeration of the feed, the moisture in the concentrate must be removed by drying before charging. The quantity of added fluxes is minimized as far as practical to save energy.

Because the residence time of the sulfide particles in the reaction chamber is only a few seconds, kinetic conditions predominate over the thermodynamic equilibrium. The reactants form a heterogeneous system, with the feed suspended in the gas flow, thus the term smelting in suspension.

These processes have several advantages:

1. High rate of reaction, increasing the production rate
2. Energy savings
3. Low volume of off-gas and correspondingly high concentration of SO₂ and low quantity of flue dust, if oxygen is used

However, a typical disadvantage is the high *copper* content of the slags, and the relatively high flue dust content in the off-gas, which can cause problem in the waste-heat boiler.

Outokumpu Flash Smelting

After a preliminary test in 1946, the first full-scale flash smelting furnace started operation in 1949 at Outokumpu Oy, Harjavalta (Finland). Flash smelting has been the most widely adopted *copper* matte smelting process since 1970. More than 40 furnaces have been installed to replace reverberatory furnaces or at new smelting operations. Nowadays the Outokumpu-type smelters account for more than 50 % of world primary smelter capacity.

Processing and Uses

The pure metal produced in refineries or remelting plants is manufactured into semifabricated products.

Working Processes

Usually *copper* is treated initially by noncutting, shaping processes to obtain semifinished products or “semis”. These processes are subdivided into hot working, cold working and, if necessary, process annealing.

Hot working means plastic forming above the recrystallization temperature. Generally *copper* is preheated to 800 – 900 °C, and the subsequent hot forming is finished at ca. 400 °C. Cast bars from modern combined continuous casting/rod-rolling systems already have sufficient temperature, thus saving thermal energy. After cooling, the hot-worked *copper* is soft *copper*. Its mechanical and electrical properties are scarcely changed, but its density has increased to nearly 8.9 g/cm³.

The next step is cold working, which involves plastic forming below the recrystallization temperature. In practice, the operation is done at room temperature. Unlike hot working, this procedure entails an essential strain hardening of the metal by increasing the number of lattice defects; however, simultaneously formed lattice voids cause a considerable decrease of electrical and thermal conductivity. After cold working, the metal is hard *copper*.

Process annealing is a heat treatment that is necessary if the hardened *copper* must be softened again, either for continued working or for producing (soft) *copper* with high electrical conductivity. Special furnaces are used for the purpose of steady heating and cooling of the metal — often in a nonoxidizing atmosphere. To achieve the intended microstructural change, the recrystallization temperature of 200 – 300 °C must be exceeded; in practice, the metal is heated to 400 – 500 °C for accelerated recrystallization. *Copper* products with exactly defined properties can be obtained if all annealing conditions are carefully controlled.

The engineering techniques are versatile. The following working methods are of special importance:

hot working cold working
hot rolling

cold rolling
extrusion

cold drawing
drop forging

cupping

Foils only ca. 0.002 mm thick are manufactured by rolling, and wires to 0.004 mm diameter by drawing. Many products of varying size are fabricated by modern variants of the extrusion process [187]. The fabrication of tubes is also quite diverse [188].

Other Fabricating Methods

In many cases, machining operations are required, e.g., cutting, turning, planing, drilling, and sawing. However, these are more important for *copper* alloys than for pure *copper* because of copper's tendency to gum. Noncontinuous casting processes are likewise more suitable for *copper* alloys because *copper* has a disadvantageous coolability. These include sand mold casting, permanent mold casting, gravity die casting, pressure die casting, and centrifugal casting. Continuous or semicontinuous casting processes, however, are well-suited for pure *copper*.

Galvanoplasty is an electrolytic operation for manufacturing complicated objects that require high precision and flawless surfaces such as hollow bodies, disk matrices, and electrotypes. A special galvanic method is *copper* plating, which involves electrolytic deposition of a thin layer of *copper*.

on another metal either for surface protection or as a base layer for electroplating with another metal (→ [Electrochemical and Chemical Deposition](#)).

Powder-metallurgical techniques are used primarily for the mass production of small pieces, especially intricate forms such as electrotechnical and mechanical structural parts. The metal powders are first compacted by pressure and then sintered in a controlled atmosphere. The *copper* powder is often mixed with other powdered metals, including those that do not form common *copper* alloys (→ [Powder Metallurgy and Sintered Materials](#)).

There are other important fabricating methods [189]. Joining is usually carried out above room temperature by soldering, brazing, or welding. Soldering may be used for all sorts of *copper*; owing to the low temperature. However, welding and brazing are feasible only with deoxidized or oxygen-free *copper*.

When tough-pitch *copper* is heated in an atmosphere containing hydrogen, the steam generated (see [Gases and Copper](#)) collects within the grain boundaries at high pressure and can destroy the grain structure by forming cracks. This phenomenon is known as “hydrogen embrittlement.”

Mechanical joining and metal bonding are also possible ways of joining *copper* with other materials.

Surface treatment of *copper* is a group of operations for surface protection or surface refinement. These include mechanical, electrical, or electrochemical handling, e.g., polishing, matte finishing, pickling by dilute sulfuric or nitric acid, metal coating or electroplating (with nickel, nickel and chromium, tin, silver, gold, or platinum metals), lacquering or coating with synthetic plastics (mainly for electrical insulation), enameling of objects (applied art), and chemical or electrochemical coloring (decoration). Coloration is effected by chemicals, mostly specially formulated metal salt solutions which form thin layers of insoluble green, red, brown, or black compounds.

Uses

Copper is a useful material with a wide range of applications because of its combination of properties. Because of its excellent electrical conductivity, it is the dominant conductor material. *Copper* is used primarily as round wire or rods, bare or insulated, for current generation, transmission, and conduction; various sorts of cables are produced for special applications. Substantial quantities of *copper* are made into generators, motors, transformers, and other electrical appliances. About 40 % of the world consumption of *copper* is for electrical purposes. As a result of its high thermal conductivity, *copper* is well-suited for vessels and pipes, especially for heating, cooling, and heat exchange.

While high-conductivity *copper* is required for electrotechnical and electronic uses, special *copper* qualities are chosen for other uses. About 30 % of world *copper* production is used for alloying. *Copper* alloys are usually cold-worked; only ca. 10 % of them are cast.

Copper is frequently used in the chemical and food industries because of its high resistance to corrosion. There is substantial use of *copper* in mechanical engineering, by fabricators of precision implements, in vehicle construction, and in ship building. There is increasing interest in *copper* building construction as a material for installation, wall lining, and roofing. Hydraulic engineers use *copper* sheets for tightening on dams, sluices (floodgates), and bridges.

Other areas of application are in the fabrication of household articles, art objects, coins and medals, and in military hardware as ammunition. There is a smaller demand for other purposes, such as electrodeposition; powder-metallurgical *copper*, special materials for brakes and self-lubricating bearings, small precision parts, filters, graphite brushes; and alloying additives for aluminum, iron,

and steel. Use in *copper* compounds, chiefly *copper* sulfate and *copper* oxides, consumes only 1 – 2 % of the primary world production.

Table 22 lists the distribution of *copper* consumption among various industries.

Table 22. Industrial use of *copper* (including alloys) in the Western world in 1995, percentage by country [190]

Branch	United States	Europe	Asia
Electrical and electronic industry	25	37.5	50
Industrial machinery and equipment	11	9	9
Building construction	43	39.5	15
Transportation	9	6.5	11
Consumer and general products	12	7.5	15

Substitution and Miniaturization. Several materials compete with *copper* and may substitute for it, depending on the relative costs. *Copper* is partly replaced by aluminum in automotive radiators and in transmission cables, high-voltage long-distance lines, and household wiring. *Copper* wires and cables for telecommunications are being displaced by microwave technology and fiber optics. *Copper* is being replaced by plastics for water pipes in both residential and commercial construction. In the area of corrosion-resistant materials, in addition to plastics there are also stainless steel and titanium.

The movement toward making smaller and smaller parts has been one of the most pervasive and continuing pressures on the *copper* market. A dramatic drop in the use of *copper* has occurred in the widespread acceptance of printed circuits. The use of wire has plummeted. The number and size of the connectors have dropped. On the other hand, miniaturization has steadily decreased the cost of the final products, thus increasing the number of units sold.

At the same time, however, this drive towards miniaturization, whether in the thickness of an automotive radiator or in the size of an electronic component, is a challenge to the *copper* industry to produce purer *copper* and more useful alloys and to the *copper* fabricating industry to produce the new miniaturized products.

In several applications *copper* is resisting substitution by using new technologies. For example in telecommunications, *copper* continues to be the preferred signal carrier for the last mile. The new xDSL (Digital Subscriber Line) technology allows the existing *copper* infrastructure of ordinary telephone wires to also carry high-speed data. The installation of optical fiber in communication trunk lines has led to a revolution in the telecom industry. *Copper* application was partly displaced, but overall this increased the demand for *copper*. Another development is the use of *copper* circuitry in silicon chip technology, which makes the microprocessors faster and lowers energy consumption. Another example is the automobile radiator, which was formerly made of *copper*, which was then displaced by aluminum. New technology was developed for producing smaller and lighter *copper* brass radiators with higher thermal conductivity than aluminum radiators. A final example for innovation in *copper* is the development of superconducting power cables made from high-temperature superconductor wire. This technology will improve energy efficiency, and now projects in Chicago and Tokyo have been started.

Process Economics

Cost of *Copper* Production and *Copper* Price. The cost of *copper* production is characterized by high capital investment in mining projects and in smelters and refineries. Mining projects are financed by large consortiums and banks. The capital investment for a green-fields smelter is in the region of 2500 – 3000 \$/t of design *copper* production. Smelter enlargement investment is approximately half that. Therefore, increased smelter production is preferably achieved by enlargement.

In the last 15 years *copper* leaching projects have been established. This is due to lower capital investment than smelters (about half), and also leaching operations built to increase the *copper* yield of ores.

Operational costs are high due to energy consumption, which is the most important factor. For primary *copper* production the overall energy consumption per tonne of *copper* is about 45 GJ, about half of which is consumed in mining and beneficiation and the rest in smelting and electrorefining. For secondary *copper*, coming for example from *copper* scrap smelting and refining, the overall energy consumption is only 20 GJ/t.

Due to several smelter enlargements, leaching operations, and also new energy-efficient milling and smelting/refining processes, the overall production cost of *copper* are falling.

The *copper* price is set primarily at the two metal exchanges: the London Metal Exchange (LME) and the New York Commodity Exchange (COMEX). Like the *copper* production cost also the *copper* prices have been in an overall declining trend since the World War II. The *copper* price also increases and decreases in the same economic cycles as industrial growth and recession. The development of *copper* prices since 1960 is shown in Figure [37](#).

Questions - New beneficiation process.

A new copper mine is being developed that contains a relatively low-grade ore, 0.6wt% Cu. The Plant Cost Index for 2008 equates to 535. The previous mine developed by your company contains 1.2 wt% Copper ore. The investment in a beneficiation process plant built in 1990 for that mine to produce 1000 t/day Cu amounted to 150 Million US\$. At the time, the Plant Cost Index was 358.

- a) Calculate a +/- 50% capital cost estimate for a beneficiation process with a 150.000 ton ore/day processing capacity for your new mine*
- b) Refine your estimate by applying the Functional Unit Method. How many functional units does your process have?*
- c) Assume the capacity restrictions indicated by Ullman (text, figure) are correct. Recalculate your estimate sub-b*
- d) Calculate a +/- 40% cost estimation using the Lang Factor method*
- e) Compare the estimates sub a,b,c and d*

Pyrometallurgical copper complex

Figure 3 gives a 'generic' flow scheme of a pyrometallurgical copper production complex.

- a) Review and discuss whether it is possible or not to arrive at a first capital cost estimate for a new production complex that processes the copper from above mine/beneficiation on the basis of the information contained in Ullmann*
- b) What method or methods could you use to arrive at a first capital cost estimate? What information would you require?*
- c) Ullmann presents 3 successive technologies that dominated the copper production scheme. Analyse this succession qualitatively using engineering economics and a life-cycle costing perspective.*

Assume in 2008 a Reverb Furnace would require 500 Million US\$ investment, operate for 30 years, and require 40 GJ/ton Cu heat, while the Outokumpu furnace require 1 Billion US\$ investment but only 20 GJ/ton Cu heat. Your company uses a 20 year period to write-off its assets.

For the following two situations: heat cost is 15 US\$/GJ and 30 US\$/GJ; interest=5%

- 1. Calculate the Discounted Cash Flow of resulting from both investments*
- 2. Calculate the Net Present Value of Both investments*

At what energy cost is the DCF the same for both options, at what energy cost the NPV?

Copper value chain

The information given spans the greater part of the copper value chain

- a) Draw a schematic of this value chain*
- b) Assume from mine to consumer 1000 US\$ added value is created. Use your knowledge of the minerals and mining industry to indicate approximately where in the chain what part of this value is created, and discuss*
- c) Ullmann indicates substitution and miniaturization are important trends affecting copper use. Discuss how these impact the value chain. What consequences do you see for copper primary producers? What strategies may they employ to improve their position?*
- d) What impacts to you foresee from the current financial crisis?*