Extractive Metallurgy of COPPER
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Preface to the sixth edition

When we began this revision in 2019, the price of copper was $2.60/lb. As we complete it today, the price is $4.38/lb. By the time you read these words, it may be back down to $2.60 again! Regardless, it has been some time since there was so much interest in the availability and technology of copper supply. The long-term prospects for the industry appear to be bright, and prospectors are scouring the globe for ore, from mountaintops in the Andes to the bottom of the oceans. The lists of top-producing mines and smelters in this book demonstrate the increase in capacity of the industry from our previous edition.

Technology advances in the industry over the previous decade have been largely evolutionary rather than revolutionary. The most significant developments include the following:

• the adoption of Chinese bottom-blown and side-blown bath smelting and converting technology;
• the creation of flowsheets for handling increasingly complex ores and concentrates;
• improved technology for processing high-strength off-gases;
• higher current densities in electrefining and electrowinning practice.

Other things have not changed. The Peirce–Smith converter is still the primary means of producing blister copper; flash furnaces are still being commissioned for concentrate smelting, and casting processes are still largely the same. Some technologies have more value than previously thought!

There has also been a change in the creative team behind this book. Matt King has decided to find other uses for his nights and weekends; in his place, we welcome to the group Dr. Gerardo Alvear Flores, currently based in Singapore. Gerardo has vast experience in the copper industry, which has taken him over his career to multiple continents and production facilities, and his experience will enhance our efforts and improve our direction.

As with previous efforts, this edition of Extractive Metallurgy of Copper is largely a product of the copper industry as a whole, since so many engineers and scientists volunteered their time and expertise (along with photographs and drawings) to make sure we got it right. Our guides included

Ken Armstrong (Chemetics)
Nigel Aslin (Glencore)
Martin Bakker (Glencore)
Michele Beacom (CIM)
Juan Carrasco (Glencore)
Preface to the sixth edition

Chunlin Chen (CSIRO)
Peter Cole (deceased) (Peter Cole Metallurgical Services)
Bernadette Currie (Rio Tinto)
Julio Flores Cantillánez (Mantos Copper)
Magnus Ek (Boliden)
Jeremy Gillis (PASAR)
Cameron Harris (Canadian Engineering Associates)
David Hazelett (Hazelett Corporation)
Enrique Herrera (Southern Peru Copper)
Shawn Hinsberger (Heath and Sherwood)
Mike Hourn (Glencore)
Chris Holding (Copper Worldwide)
John Hugens
John Hugens, Jr. (Hugens Metallurgy)
Evgeni Jak (University of Queensland)
Hugo Joubert (Tenova Pyromet)
Akira Kaneda (Mitsubishi Materials)
Matt King (Worley Parsons)
Michael Marinigh (Heath and Sherwood)
Leopoldo Mariscal (Mexicana de Cobre)
Jorge Meza (Southern Peru Copper)
Yoshihiro Mine (Mitsui Mining & Smelting)
Enrique Miranda (IIMCH)
Michael Moats (Missouri University of Science and Technology)
Anthony Mukutuma (First Quantum Minerals)
Kensaku Nakamura (JX Nippon Mining and Metals)
Takeshi Nakamura (Tohoku University)
Stanko Nikolic (Glencore)
Yerzhan Ospanov (Kazakhmys)
Lauri Palmu (Metso Outotec)
John Parker (Process Ideas)
Joe Pease (Minerales)
Beatrice Pierre (Glencore)
Nikola Popovic (Glencore)
Yves Prevost (Glencore)
Venkoba Ramachandran
Pedro Reyes (Anglo American)
Carlos Risopatron (International Copper Study Group)
Joanne Roberts (Freeport McMoRan)
Tim Robinson (Metso Outotec)
Gerardo Sanchez (Codelco)
Maxsym Shevchenko (University of Queensland)
Etsuro Shibata (Tohoku University)
Denis Shishin (University of Queensland)
Alfred Spanring (RHI AG)
Andreas Specht (Aurubis)
Hitoshi Takano (Sumitomo)
Supriya Upadhyay (Rio Tinto)
Maurits Van Camp (Umicore Precious Metals Recycling)
Nicole Witaslawsky (International Copper Association)
Yutaka Yasuda (JX Nippon Metals and Mining)
Gabriel Zárate (Jetti Cobre)
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CHAPTER 1

Overview

1.1 Introduction

Copper is most commonly present in the earth’s crust as copper–iron–sulfide and copper sulfide minerals, primarily chalcopyrite (CuFeS₂) and chalcocite (CuS₂). The concentration of these minerals in a mine is low. Typical copper ores contain from 0.3% Cu (open pit mines, Fig. 1.1) to 1.7% Cu (underground mines, Fig. 1.2). The rest is noneconomic rock. Pure copper metal is mostly produced from these ores by concentration, smelting, and refining (Fig. 1.3).

Copper also occurs to a lesser extent in oxidized minerals (carbonates, oxides, hydroxysilicates, sulfates). Copper metal is usually produced from these minerals by leaching, solvent extraction, and electrowinning (Fig. 1.4). These processes are also used to treat chalcocite (Cu₂S).

Figure 1.1 Open pit Cu mine. Note the new blast holes, top right, and blasted ore to the left of them. The shovel is placing blasted ore in the truck from where it will go to processing. The water truck is suppressing dust. The front-end loader is cleaning up around the shovel. The shovel is electric. Its insulated power wire mostly lies on the surface except over the wire bridge under which all vehicles travel to and from the shovel. (Photograph courtesy of Freeport–McMoRan Copper & Gold Inc.).
A third major source of copper is scrap copper and copper alloys. Yearly production of copper from recycled used objects is 15–20% of mine production. In addition, there is considerable remelting and refining of scrap generated during fabrication and manufacture. Total copper production in 2018 (mined and from end-of-use scrap) was 25 million tonnes.

This chapter introduces the principal processes by which pure copper is extracted from ore and scrap. It also indicates the relative industrial importance of each. Finally, it discusses worker safety—because it is so important.

1.2 Ore—rock differentiation in the mine

A mine consists of regions of economic ore and regions of noneconomic rock, e.g., quartz and feldspar (Berger et al., 2008). These regions are located by drilling, sampling, and analyzing the drill core for Cu. Where possible the noneconomic rock is not mined. When the mine can only be developed by mining intertwined ore and rock, the ore is sent to copper production and the rock goes to waste heaps. The material at the ore/rock boundary is carefully sampled and analyzed to ensure that ore is not mistakenly sent to the waste rock heaps.
Sulfide ores (0.5 - 2.0% Cu)

Comminution

Flotation

Concentrates (20 - 30% Cu)

Other smelting processes*

Submerged tuyere smelting

Drying

Flashing smelting

Submerged lance smelting

Matte (50-70% Cu)

Converting

Blister Cu (99% Cu)

Anode refining and casting

Anodes (99.5% Cu)

Electrorefining

Cathodes (99.9% Cu)

Melting

Molten copper

Continuous casting

Fabrication and use

Figure 1.3 Main processes for extracting copper from sulfide ores. Parallel lines indicate alternative processes. *Principally Mitsubishi and Vanyukov smelting. ——— ———and various small Chinese processes.
$\text{H}_2\text{SO}_4$ leach solution, recycle from solvent extraction, $\sim 0.4 \text{ kg Cu/m}^3$

Make-up $\text{H}_2\text{SO}_4$

$\sim 10 \text{ kg H}_2\text{SO}_4/\text{m}^3$, $\sim 0.4 \text{ kg Cu/m}^3$

Ore 'heap'

Collection dam

Pregnant leach solution, 2 to 5 kg Cu/m$^3$

Solvent extraction

Electrolyte, 45 kg Cu/m$^3$

Electrowinning

Stripped cathode plates, 99.99% Cu

Melting

Molten copper

Continuous casting

Fabrication and use

Figure 1.4 Flowsheet for leaching oxide and Cu$_2$S ores. The dissolved Cu is recovered by solvent extraction purification followed by electrowinning. Leaching accounts for $\sim 20\%$ of primary (from ore) copper production.
1.3 Extracting copper from copper–iron–sulfide ores

About 80% of the world's mined copper originates in chalcopyrite (CuFeS$_2$) ores. Chalcopyrite is extremely difficult to dissolve in aqueous solutions, so the vast majority of copper extraction from these ores is pyrometallurgical. Extraction by this approach entails

(a) isolating the ore’s Cu–Fe–S and Cu–S mineral particles in a concentrate by froth flotation
(b) smelting this concentrate to molten high-Cu sulfide matte
(c) converting (oxidizing) this molten matte to impure molten blister copper
(d) fire- and electrorefining this impure copper to ultrapure copper.

Increasingly, smelting and converting are being combined, especially in China.

1.3.1 Concentration by froth flotation

Copper ores being mined in 2020 are far too dilute in Cu (0.3%–1.7%) to be smelted directly. Heating and melting their huge quantity of waste rock would require prohibitive amounts of fuel. The rock would also produce impossibly large amounts of molten oxide slag. Fortunately, the ore’s Cu–Fe–S and Cu–S minerals can be isolated by physical means into high-Cu concentrate, which can then be smelted economically.

The most effective method of isolating the Cu minerals is froth flotation. This process causes small Cu–Fe–S and Cu–S mineral particles to become attached to air bubbles rising through a finely ground ore slurry (Fig. 1.5). Selectivity of flotation is created by

![Figure 1.5](image_url)

Figure 1.5 Schematic view of flotation cell. Reagents cause Cu–Fe sulfide and Cu sulfide minerals in the ore to attach to rising air bubbles, which are then collected in a short-lived froth. This froth is dewatered to become concentrate. The unfloated waste passes through several cells before being discarded as a final tailing. Many types and sizes (up to 300 m$^3$) of cell are used (Chapter 3).
using chemical reagents (collectors) that make the Cu minerals water-repellent while leaving waste minerals covered by water (i.e., wetted).

This water repellency causes Cu mineral particles to attach to the flotation cell’s rising bubbles while the other mineral particles remain unfloated. The floated minerals overflow the cell in a froth that, when dewatered, becomes \( \sim 25\% \) Cu concentrate. The low-Cu waste rock particles underflow the cell. They are dewatered and sent to tailing ponds.

Flotation is preceded by crushing and grinding the mined Cu ore to small (\( \sim 100 \mu m \) diameter) particles. Its use has led to adoption of smelting processes that efficiently smelt finely ground solids.

A video of mining and mineral processing may be seen in *The Mining Process at Copper Mountain Mine*. This mine produces 30,000 tonnes of ore and 160,000 tonnes of waste rock per day.

### 1.3.2 Matte smelting

Matte smelting oxidizes and melts flotation concentrate in a large, hot (1250°C) furnace (Figs. 1.3 and 1.6). The objective of the smelting is to oxidize S and Fe from the Cu–Fe–S concentrate to produce an intermediate Cu-enriched molten sulfide matte. The oxidant is oxygen-enriched air. Example reactions are

\[
2 \text{CuFeS}_2(s) + 3.25 \text{O}_2(g) \rightarrow \text{Cu}_2\text{S} - 0.5\text{FeS(ℓ)} + 1.5 \text{FeO(s)} + 2.5 \text{SO}_2(g)
\]

\(30 \, ^\circ\text{C}\) \hspace{1cm} \(1220 \, ^\circ\text{C}\)

Example reaction (1.1)

\[
\text{in concentrate} \quad \text{in oxygen–enriched} \quad \text{molten matte} \quad \text{iron oxide} \quad \text{in offgas}
\]

Figure 1.6 Metso Outokumpu oxygen-enriched air flash furnace. Flash furnaces are typically 20 m long and 7 m wide. They smelt 1000–3000 tonnes of concentrate per day.
Simultaneously, the iron oxide is fluxed with quartz to give a low melting point molten slag. A representative reaction is

\[
\begin{array}{ccc}
1220^\circ C & 30^\circ C & 1250^\circ C \\
1.5 \text{FeO(s)} + 0.75 \text{SiO}_2(s) + \text{heat} & \rightarrow & 0.75 \text{Fe}_2\text{SiO}_4(\ell) \\
\text{iron oxide} & \text{in rock and} & \text{molten slag} \\
\text{quartz flux} & \end{array}
\]

(1.2)

The concentrate’s gangue (waste rock) minerals also dissolve in the molten slag. Reactions (1.1) and (1.2) are both exothermic; they supply most of the smelting process’s heat requirement.

The products of smelting are (a) molten sulfide matte (55%—70% Cu) containing most of the Cu in the concentrate and (b) molten oxide slag with as little Cu as possible. The molten matte is subsequently converted (oxidized) in a converting furnace to form impure molten copper. The slag is treated for Cu recovery, then discarded or sold (Chapter 10).

SO\(_2\)-bearing offgas (10—60 volume% SO\(_2\), remainder mostly N\(_2\)) is also produced. SO\(_2\) is harmful to flora and fauna, so it must be removed before the offgas is released to the atmosphere. This is done by capturing the SO\(_2\) as sulfuric acid (Chapter 11).

Matte smelting is mostly done in flash furnaces (Fig. 1.6). It is also done in top lance and submerged tuyere furnaces (Chapter 6). Three smelters smelt Cu-rich concentrate directly to molten copper (Chapter 10). This is unusual because single-furnace smelting with normal (25% Cu) concentrate produces too much high-Cu slag.

1.3.3 Converting

Copper converting is oxidizing the intermediate molten matte from smelting with air or oxygen-enriched air. It removes Fe and S from the matte to produce crude (99% Cu) molten copper. This molten copper is subsequently sent to fire- and electrorefining.

Most converting is done in cylindrical Peirce—Smith converters (Fig. 1.7a), but newer continuous converting processes are eating into this dominance (Chapter 8).

1.3.3.1 Peirce—Smith converting

Peirce—Smith converting entails pouring large ladles of molten smelting furnace matte (1220\(^\circ\)C) into a cylindrical converter through a large central mouth (Fig. 1.7b). The oxidizing oxygen-enriched air blast is then started and the converter is rolled, forcing the blast into the molten matte through a row of tuyeres along the length of the vessel. The heat generated in the converter by Fe and S oxidation is sufficient to make the process autothermal.
The converting takes place in two sequential stages:

(a) the FeS elimination or slag-forming stage:

\[
\begin{align*}
1220 \, ^\circ C & \quad 30 \, ^\circ C & \quad 30 \, ^\circ C & \quad 1200 \, ^\circ C & \quad 1200 \, ^\circ C \\
2 \text{FeS} & + \quad 3 \text{O}_2(g) & + \quad \text{SiO}_2(s) & \rightarrow \quad \text{Fe}_2\text{SiO}_4(\ell) & + \quad 2 \text{SO}_2(g) & + \quad \text{heat}
\end{align*}
\]

in molten matte in air blast in quartz flux molten slag in offgas

Figure 1.7a Peirce–Smith converter for producing molten “blister” copper from molten Cu–Fe–S matte. Typical production rates are 200–600 tonnes of copper per day. Oxygen-enriched air or air “blast” is blown into the matte through submerged tuyeres. Silica flux is added through the converter mouth or by air gun through an endwall. Offgas is collected by means of a hood above the converter mouth. (From Chapter 2.1 - Copper Production in Treatise on Process Metallurgy, Volume 3: Industrial Processes, 1st Edition, Copyright Elsevier 2013 Pages 534—624).

Figure 1.7b Positions of Peirce–Smith converter for charging, blowing, and skimming. SO\textsubscript{2} offgas escapes the system unless the hooding is tight. A converter is typically 4 or 4.5 m diameter. (Credit: Used with permission from Mettop, https://mettop.com/api/cdn/uploads/1493364462_7v372frw.pdf Figure 4).