Preface

Extractive metallurgy is the art of extracting metals from their ores and refining them.

This book deals with the processes, operations, technologies and processing routes of extractive metallurgy, i.e. the (production) extraction of metals from ores, concentrates (enriched ores), scraps and other sources and their refining to liquid metals before casting or to solid metals.

In many books dealing with metallurgy, the introduction starts by recalling the steps of the progress of metallurgy. These steps, according to and since Lucrèce, are identical to those of human progress: the copper age, the bronze age, the iron age, the silicon age[1]. According to Mohen[2], the considerable role attributed to the three principal metals in the development of human societies must not be overstressed or overvalued. It is nonetheless true that "metallurgy is the most advanced prehistoric manifestation of the mastery of natural resources" (Mohen). Extracting copper from its ore dates back to the middle of the fifth millennium before our age and extracting iron from its ore dates from the beginning of the second millennium before our age.

The winning (production) of metals and alloys today is still one of the basic industries of the transformation of matter. Metals and alloys still are essential resources for metallic, mechanic, electromagnetic, electric and even electronic industries (silicon is treated as a metal).

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[1] S.L. SASS, *The Substance of Civilization: Materials and Human History from the Stone Age to the Age of Silicon*, Arcade Publishing, 1999.

[2] J.P. MOHEN, *Métallurgie préhistorique*, Masson, Paris, 1990.

This industry is characterized by:

– Production (of primary metal) ranging from 1,345 million tons (Mt) of steel a year to 138,000 tons of titanium, in 2007[3].

Steel	Aluminum	Copper	Zinc	Lead	Nickel	Magnesium	Titanium
1,345	38	15.6	10.6	7.0	1.66	0.79	0.138

Table 1. *World metal production in 2007*

– Very high growth rates in the years 1950 to 1973, and again since 2000. The production of steel was 200 million tons in 1950. The production of aluminum increased from 2 million tons in 1950 to 10 million tons in 1973, reaching 38 million tons in 2007. If in developed countries the growth in terms of tonnage has strongly slowed in recent decades, this is due to a smaller consumption of these products owing to the increase in mechanical and physical properties of the materials and parts forged from these materials, thus requiring less material for the same usage. However the annual production of steel in China increased from 182 million tons in 2002 to 489 million tons in 2007[4].

– Production costs varying by a factor of 20 to 25 between steel and titanium. The three principal costs in metal production are investment, ore and energy consumption. The energy consumption is about 20 GJ/ton of steel, 80 GJ/ton of aluminum and 160 GJ/ton of titanium. Hence the permanent research into improvements of the processes or operations and/or the development of new processes.

– Very high recycling rates. Recycled steel represents 46% of iron sources in worldwide steel production. The “electric furnace processing route” produces 35% of steel. It uses 75% less energy than the integrated route. The recycling rate of aluminum represents 25% of total production and the energy consumption from recycled aluminum represents 5% (energy reflow) of energy consumption from the ore. The production of primary zinc is 7.4 million tons and from recycled zinc is 2.1 million tons. In the case of lead, the production from recycled lead is greater than 50%.

– Very high quality products with degrees of purity (i.e. contents of harmful impurities) for the finished products, comparable to the purity of materials for electronics and with very narrow concentration ranges of the alloying elements, to obtain physical or mechanical properties with very small dispersions. For metal castings reaching 300 tons, steel grades with carbon content of less than 25 ppm,

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[3] US Geological Survey, *Minerals Commodity Summaries and Minerals Yearbook*, 2007.

[4] Source: IISI (International Iron and Steel Institute).

and sulfur and phosphorus content of less than 20 ppm or even 10 ppm can be guaranteed. The impurities in liquid aluminum after electrolysis and refining are <3 ppm for Li, <1 ppm for Ni and <1/10 ppm for H. The contents of each impurity in copper for electric wire must be <1 ppm. Achieving these chemical performances coupled to research into the lowest energy consumption requires perfect mastery of the process and thus a profound knowledge of its technology.

– The energy consumption and reduction of pollution (rejected CO_2, SO_2 and dust) from the production of metals have become major objectives, leading to the development of new processes or product lines.

– Non-ferrous metal ores often have very low contents of many rare or noble metals, whose extraction and recuperation often constitutes essential steps for the global production economy. Such extraction requires very complex processing routes for recovering rare or precious metals.

Often the metal can or could be produced via several processing routes. The industrial processing routes for a given metal are to a large extent dependent on economic considerations, i.e. the cost of raw materials, cost of energy, cost of equipment and market conditions.

The raw materials for the production of metals and alloys are the ores on one hand and recovered and recycled products on the other:

– the ores. The ores of Sn, Fe, Mn, Cr, Al, Ni are oxides. The ores of many non-ferrous metals, e.g. Cu, Ni, Pb, Zn, Cd, Mo, are sulfides;

– the recycled metals (Fe, Al, Cu, Zn, Pb);

– the steel plant dust containing metals or oxides (Zn, Cd, Pb);

– the residues from leaching operations, e.g. the red muds, a residue containing titanium, vanadium, gallium produced by bauxite leaching during the Bayer process, the gold cyanide sludge;

– the drosses, slags and scoria treated to recover rare metals or to eliminate harmful components.

The operations of mineralogy are known as ore-dressing. In the general case, the ore must be concentrated to free it from minerals of no value, called the gangue, whose main components are oxides (SiO_2, Al_2O_3, CaO, MgO). This is done using physical operations: grinding (comminution) or fragmentation of the ore to small sizes to allow easy separation, then separation by sedimentation and enrichment by flotation, magnetic sorting etc., leading to a raw material enriched in components.

The operations of extractive metallurgy treat ores, concentrates and recycled metals. These are mixtures of oxides or sulfides. The processing routes of the ore’s treatment, raw or enriched, together with the technologies used in these routes depend first of all on the ore's nature and its metal content.

Thus iron ore is practically pure iron oxide (hematite or magnetite), with a content of iron of the order of 65% and several percent of silica (SiO_2). The basic treatment will be the direct reduction of the iron oxide.

Alternatively, the ores can be treated to give an essentially pure chemical compound of the metal and this compound may be converted to give the metal. For example, aluminum's ore (bauxite), is composed of alumina (Al_2O_3, 30–60%), iron oxide (Fe_2O_3, 1–30%) and silica (1–10%). The first phase of the ore's treatment will be the separation of these oxides to obtain the pure alumina, which will be reduced in a second phase by electrolysis in molten salts.

The copper sulfide ores, whose copper content is very low, exceptionally reaching 5%, undergo processes of mineralogy (flotation) to obtain concentrates containing Cu (20–25%), Fe (30%) and S (30%). The separation of copper sulfide from iron sulfide via a selective roasting constitutes the first step of the treatment. The second step is a copper converting.

Zirconium ore, zircon (silicate of zirconium and hafnium, i.e. $ZrSiO_4$ and $HfSiO_4$), is converted into gas chlorides whose separation is possible before the reduction of zirconium chloride to very pure zirconium.

Extraction and refining operations may be carried out by pyrometallurgical, hydrometallurgical, halide and electrometallurgical processes:

– *pyrometallurgy* involves processes carried out at high temperatures divided into:

  - *primary pyrometallurgy*, which converts the ore or concentrate to impure metal generally in liquid form. The main operations are oxide reduction, sulfide roasting, smelting and converting;

  - *secondary pyrometallurgy* is the treatment of the liquid metal, obtained either directly in the first step or by remelting metallic recycled products. It consists of several refining operations, mainly the removal of harmful elements left in the liquid metal (deoxidation, dehydrogenation, etc.) and addition of the alloying elements;

– *hydrometallurgy* consists of operations of primary metallurgy performed in aqueous solutions, at relatively low temperatures and often under high pressure, such as leaching, precipitation and solvent extraction;

– *hydroelectrometallurgy* consists of salt electrolysis in an aqueous solution, yielding the metal in a solid state. Electrorefining constitutes a refining process of the metal obtained in a first electrolysis;

– *pyroelectrometallurgy* consists of processes employing electrolysis (reduction), either of mattes or oxides (e.g. Al_2O_3) or chlorides (e.g. $MgCl_2$) into molten salts, yielding the metal in a liquid state;

– *chlorometallurgy* consists of the following processes:

  - *chlorination* of a highly reactive metal oxide, such as titanium or zirconium,

  - *separation* of the chlorides via physical processes: distillation and extractive distillation,

  - *reduction* of chlorides by metallothermic reduction.

The upholding into operation of an existing processing unit, the improvement of an industrial operation, the implementation of a new technology (not formerly used in the unit) and the development of a new process all fall within technical considerations, as well as economic considerations. In this series, economical considerations will not be discussed, for obvious reasons, but sound economic decisions rest on in-depth technical analyses of the processes and operations. Such in-depth analyses are based on process engineering principles. These methods use mathematical models allowing us to simultaneously take into account the elementary processes and their couplings[5]. These mathematical models are sets of fundamentally-based differential equations derived from thermodynamics, kinetics, heat flow, fluid flow, mass transfer and electromagnetic phenomena. Modeling will thus be at the heart of all the analyses here. The solutions to these differential equations, via analytical or numerical methods, allow us to achieve sound quantitative previsions. Analytical solutions of these equations of partial derivatives have been established in numerous instances, but only for specific cases. They are nonetheless interesting as they reveal the influence of certain factors or parameters on the processes. This leads to very useful dimensionless numbers. These analytical solutions and the dimensionless equations are presented and used in these volumes. For the numerical methods of the solution of equation systems, the reader is referred to specialized publications.

The subject of extractive metallurgy is also addressed in two other publications written by myself and published by ISTE. The first volume, *Basic Thermodynamics and Kinetics* deals with the fundamentals of thermodynamics and kinetics of the extraction processes. The second volume, *Metallurgical Reaction Processes,* deals with the extraction and refining unit processes. This final volume, *Processing Operations and Routes*, deals with the operations and technologies used in industrial

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[5] J. SZEKELY, “The mathematical modeling revolution in extractive metallurgy”, *Metallurgical Transactions B*, Vol. 19B, p. 525-540, 1988, and H.Y. SOHN, “The coming-of-age of process engineering in extractive metallurgy”, *Metallurgical Transactions B*, Vol. 22B, p. 737-754, 1991.

production and industrial processing routes, i.e. the combination of steps or operations used to convert the available ore to metal, illustrated by flowsheets.

This book is intended not only for students of metallurgical and mechanical engineering who want to acquire the bases of this technology, decreasingly taught in universities and engineering schools, but also for engineers confronted with a new production problem, either directly (management of a industrial operation or development of a new process) or indirectly (in the definition of a materials' specification).

It is conceived to be accessible to any student or engineer with general chemistry and physics training. It only necessitates elementary knowledge in chemistry, thermodynamics and chemical kinetics. One of the objectives of this book is to allow the easy consultation of books and technical publications dealing with this field.

This book is the result of my chemical engineering training, courses taught in the Écoles des Mines of Nancy and Paris (France), visits to industrial plants, research performed in collaboration with industry, studies and common work as a consultant and as an industrialist in direct contact with numerous producers of metallic parts. I would like to thank, more particularly, engineers from the research centers of Arcelor-Mittal (IRSID), Alcan (ex-Péchiney), Cezus and Eramet for their advice and authorized opinions.

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