

Metallurgical Furnaces

For other industrial reactors and their applications, see → Stirred-Tank and Loop Reactors, → Tubular Reactors, → Fixed-Bed Reactors, → Fluidized-Bed Reactors, → Bubble Columns, → Three-Phase Trickle-Bed Reactors, → Reaction Columns, → Thin-Film Reactors, and → Biochemical Engineering.

JÖRG GRZELLA, Lurgi AG, Frankfurt, Federal Republic of Germany (Chaps. 1, 3, 4)

PETER STURM, Lurgi AG, Frankfurt, Federal Republic of Germany (Chap. 2)

JOACHIM KRÜGER, Institut für Metallhüttenwesen und Elektrometallurgie, Rheinisch-Westfälische Technische Hochschule, Aachen, Federal Republic of Germany (Chap. 5)

MARKUS A. REUTER, Institut für Metallhüttenwesen und Elektrometallurgie, Rheinisch-Westfälische Technische Hochschule, Aachen, Federal Republic of Germany (Chap. 5)

CARINA KÖGLER, Institut für Metallhüttenwesen und Elektrometallurgie, Rheinisch-Westfälische Technische Hochschule, Aachen, Federal Republic of Germany (Chap. 5)

THOMAS PROBST, Institut für Metallhüttenwesen und Elektrometallurgie, Rheinisch-Westfälische Technische Hochschule, Aachen, Federal Republic of Germany (Chap. 5)

1.	Rotary Kilns	2	5.1.2.	Electrothermal Furnaces	17
1.1.	Design	2	5.1.3.	Energy Consumption and Production Capacities	19
1.1.1.	General	2	5.1.4.	Economic Aspects	20
1.1.2.	Structural Elements	2	5.2.	Resistance Furnaces	20
1.2.	Process Engineering	3	5.2.1.	Basic Principles	20
1.3.	Applications	4	5.2.2.	Reduction Resistance Furnaces	22
1.3.1.	Roasting and Calcining	4	5.2.2.1.	Furnace Construction and Operating Parameters	22
1.3.2.	Calcination of Limestone, Dolomite, and Magnesite	4	5.2.2.2.	Metallurgical Significance	24
1.3.3.	Production of Cement Clinker	4	5.2.3.	Refining Resistance Furnaces	26
1.3.4.	Iron Ore Reduction	5	5.2.4.	Solid-State Resistance Furnaces	28
1.3.5.	Volatilization Processes	6	5.3.	Arc Furnaces	29
1.3.6.	Other Applications	6	5.3.1.	Basic Principles	29
2.	Multiple-Hearth Furnaces	6	5.3.2.	Electric Arc Furnaces	29
2.1.	Description	8	5.3.3.	Vacuum Arc Refining (VAR) Furnaces	30
2.2.	Applications	9	5.4.	Induction Furnaces	31
2.2.1.	Roasting of Sulfide Ores	9	5.4.1.	Basic Principles	32
2.2.2.	Use for Endothermic Reactions	10	5.4.2.	Furnace Construction	33
2.2.3.	Clarifier Sludge Treatment	10	5.4.2.1.	Crucible Induction Furnace	33
3.	Shaft Furnaces	11	5.4.2.2.	Channel Induction Furnace	34
4.	Smelting, Melting, and Refining in Bath and Flash Smelting Reactors	13	5.4.2.3.	Special Induction Furnaces	37
4.1.	Bath Smelting Furnaces	14	5.5.	Plasma Furnaces	37
4.2.	Flash Smelting Furnaces	14	5.6.	Electron-Beam Furnaces	38
4.3.	Bath Melting and Refining	14	5.7.	Fused-Salt Electrolysis Cells	40
4.4.	Converters	15	5.8.	Modeling	42
5.	Electrothermal Reactors	16	6.	References	42
5.1.	Introduction	16			
5.1.1.	History	16			

1. Rotary Kilns

A rotary kiln is an inclined, rotating cylindrical reactor through which a charge moves continuously. The rotary kiln is used when thermal processing of solids that is more severe than drying is required [1]. The furnace walls (normally lined) make intermittent contact with the flue gas and the charge. Heat required for the various physical and chemical processes is delivered to the charge by lifting and overturning the charge as it moves through the interior of the rotary kiln [2].

The first proposal for using a furnace defined in this way is probably that found in an English patent from 1865 [1]. The most widespread application of this principle today, the production of cement clinker, began in 1885 [3], [4]. Nowadays, limestone calcining [138], iron ore reduction, and PbZn volatilization, mainly from electric arc furnace dust [134], [135] are important too.

1.1. Design

1.1.1. General

The essential design elements of a rotary kiln are depicted in Figures 1 and 2. The rotary kiln consists of a lined hollow cylinder, mounted in an inclined position on rolls and rotated slowly by a drive. The charge material moves from the feed end to the discharge as a result of the rotary motion and gravity. The inclination is between 1.5 and 5% and varies only in experimental kilns. Speed is between 0.2 and 2 rpm; variable-speed drives used to control the residence time are common.

Kiln diameter is usually constant over the full length. Diameters have increased to more than 7 m, especially in the cement industry; kilns for wet cement processing can be more than 200 m long.

Some rotary kilns have internals such as conveying or lifting flights, built in crossed-hanging link chains, or ring dams. In some processes, air-feed pipes or burner tubes for gas or oil are installed on the furnace shell. Air or other gases can also be introduced through ports in the lining.

1.1.2. Structural Elements

The *steel shell* of the kiln (Fig. 2, b) is conically tapered at the ends and may have other tapered sections. It experiences torsion due to the drive, and flexural stress due to its own weight and the weight of the lining and charge. Because of partial filling and pointwise support, the ideally circular shell cross section is deformed into an oval shape. The shell is designed in accordance with the laws of thin-shell statics or by approximation methods [5–12].

The *riding rings* (Fig. 2, a) that help support the furnace shell are one-piece steel castings. Field-welded riding rings have also been used [13]. Riding rings up to a diameter of 5 m are welded to the shell in some designs. Toothed riding rings are also common. Usually, however, especially in large-diameter units, riding rings are slipped loosely onto the thickened shell ring. The riding ring moves relative to the shell when in rotation. Correct sizing of the riding ring, play, and shell ring thickness are crucial for lining life in a kiln section; this represents a difficult design problem [14], [15]. Measurements of oval deformation with the “shell tester” aid the designer [16–18]. Careful installation and maintenance of kilns, most of which are supported at several points, are also important. The alignment of long rotary kilns is critical for the load distribution on the riding rings and the shell [19–21].

Two smooth *trunnion rolls* (Fig. 2, d) per riding ring, shrunk onto journals, generally turn in plain bearings with immersion or pressure-flow lubrication. Antifriction bearings have also been used.

One or more *thrust rolls* (Fig. 2, f) arranged parallel to the kiln axis, bear the downslope forces exerted by the kiln. These have hydraulic position adjustments so that the kiln can be moved in the longitudinal direction.

The kiln is rotated by a *gear ring* (Fig. 1, j) that is elastically attached to the shell and is driven by one or two pinions (depending on the drive torque, (Fig. 1, k). Frequency-controlled multiphase motors allow continuous control of rotational speed with very little loss of energy. In case of malfunction, mechanically or electrically actuated couplings can be used to engage an auxiliary drive (electric or internal combustion motor) to keep the kiln turning slowly and

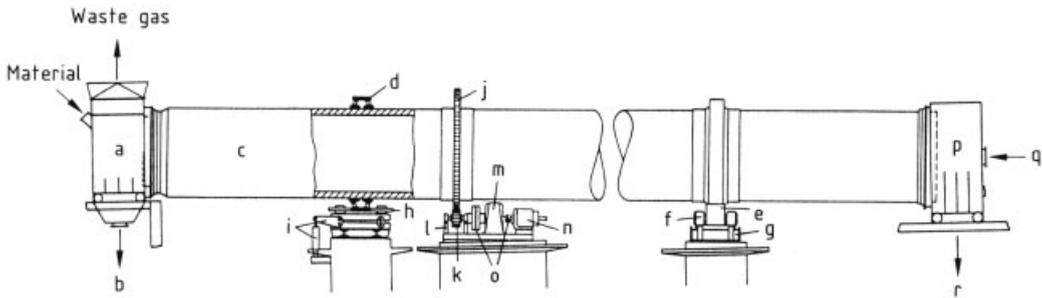


Figure 1. Schematic of a rotary kiln [50]

a) Kiln inlet head; b) Dust discharge; c) Rotary kiln; d) Riding ring; e) Roller; f) Roller bearing; g) Base plate; h) Thrust roller; i) Hydraulic system; j) Gear ring; k) Pinion; l) Pinion bearing; m) Gear box; n) Drive; o) Coupling; p) Kiln discharge head; q) Central burner; r) Discharge

prevent damage due to overheating on one side [21], [22].

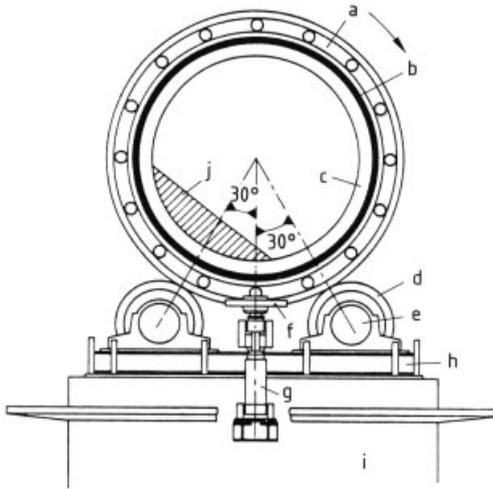


Figure 2. Section through kiln support [50]

a) Riding ring; b) Kiln shell; c) Lining; d) Trunnion roller; e) Roller bearing; f) Thrust roller; g) Hydraulic system; h) Base plate; i) Plinth; j) Charge

An important component of the rotary kiln is the *lining* (Fig. 2, c). Its thickness, physical properties, and chemical composition are dictated by the process to be carried out. For example, a cement kiln usually has a magnesite brick lining in the clinker zone and acid-insulating brick made from silicate compounds in the preheating zone. In iron ore reduction, low-iron alumina or magnesium – spinel bricks are required [23], [24]. An important factor determining the service life of the bricks is the mechanical stability of the shell [25]. Interlocking bricks (with tapered groove and tongue) are used in large-

diameter rotary kilns [26], [27]. Qualities and lining techniques have improved greatly and the service life of linings has been extended significantly [28], [29]. Insulating liners would be very desirable for heat retention but have not proved useful in kilns with more than 3.6 m diameter.

1.2. Process Engineering

Movement of Material. The rotary kiln carries out several functions simultaneously: it is a device for conveying, mixing, heat transfer, and reaction. These functions must be in harmony. The charge in the kiln moves both radially and axially. Radial motion is determined by the degree of filling (percentage of cross-sectional area occupied by the charge) and the rotational speed. The angle of repose and the kiln inclination govern axial motion.

The interior of the charge tends to have a higher bulk density than the exterior, and grain size increases toward the outside [30]. This tendency can be counteracted by the internals, which also improve heat transfer into the charge. Dust production can be limited by pelletizing the feed.

Heat transfer occurs principally from the combustion gas (generated by a burner usually installed at the discharge end of the kiln) to the charge. The driving force is generally the temperature difference. The gas can move co- or countercurrent to the longitudinal motion of the charge. Cocurrent gas flow is advantageous only when the charge temperature does not have to

exceed a certain value. The countercurrent arrangement is preferred because it involves an increased total energy consumption. The different types of heat transfer in a rotary kiln are shown in Figure 3. Fundamental work is reported in [136], [137].

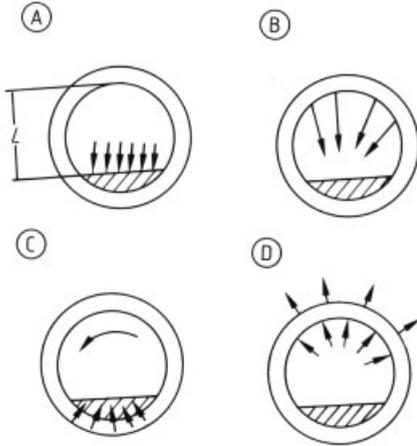


Figure 3. Types of heat transfer in a rotary kiln

A) Heat transfer to material by gas radiation and convection; B) Heat transfer to material by brick radiation; C) Conductive heat transfer to material from brick; D) Heat transfer to brick by radiation, convection, and heat loss by shell radiation and convection

1.3. Applications

1.3.1. Roasting and Calcining

Rotary kilns were employed for the exothermic roasting of sulfidic ores and for the endothermic removal of water of hydration and carbon dioxide from fine-grained materials such as ores, phosphates, alumina, ilmenite, and titanium dioxide. Today these processes are performed almost exclusively in fluidized-bed reactors (\rightarrow Fluidized-Bed Reactors), which offer better heat- and mass-transport conditions.

However, rotary kilns have advantages where softening, sticking, or even partial melting of the material cannot be avoided.

1.3.2. Calcination of Limestone, Dolomite, and Magnesite

Whereas coarsely crushed limestone can be converted to quicklime by heating in the shaft furnace, the rotary kiln is preferred for particle sizes

≤ 60 mm because it delivers a more uniform product at a higher rate (\rightarrow Lime and Limestone, Chap. 3.3.2.). This quicklime is particularly suitable for steelmaking and has been used in flue-gas desulfurization since the 1980s [31], [138].

Typical dimensions of rotary kilns with a quicklime capacity of 560 t/d are

Kiln without preheater	145 m \times 3.45 m diameter
Kiln with vertical preheater	56 m \times 4.0 m diameter

The rotary kiln also competes with the shaft furnace in the production of sintered magnesite and dolomite (\rightarrow Magnesium Compounds, Chap. 4.2.5.). As in limestone calcination, the rotary kiln offers the advantage of handling charge material of finer size with a broad size range (e.g., 2–60 mm) and can also handle throughputs at high calcination temperature (1600–1900 °C). A rotary kiln 170 m long with a shell diameter of 4.5 m, used for the production of sintered magnesite, is reported to have a capacity of 530–600 t/d. The same author indicates that the same mathematical relationships cannot be used for the design of cement, dolomite, and magnesite kilns [32].

1.3.3. Production of Cement Clinker

Cement is produced almost exclusively in rotary kilns (\rightarrow Cement and Concrete, Chap. 1.4.3.). World production was ca. 730×10^6 t in 1976 [33] and 1363×10^6 t/a in 1994 (USA 188×10^6 t/a, Europe 251×10^6 t/a). Developments in clinker production have, therefore, always spurred rotary kiln technology as a whole. Energy accounts for as much as 50 % of the total production costs of cement clinker [34]. Energy-saving approaches have led to thermally sophisticated, large-capacity units. The trend is also toward using coal as the energy source. Long rotary kilns with slurry feed (Fig. 4 A) have increasingly been replaced by “heat-exchanger” kilns (Figs. 4 B, C) in which the raw meal is heated in upstream suspension-type heat exchangers [36–38]. Development work with improved dust collection systems has led to energy consumption in the order of 3.35 MJ per kilogram of clinker.

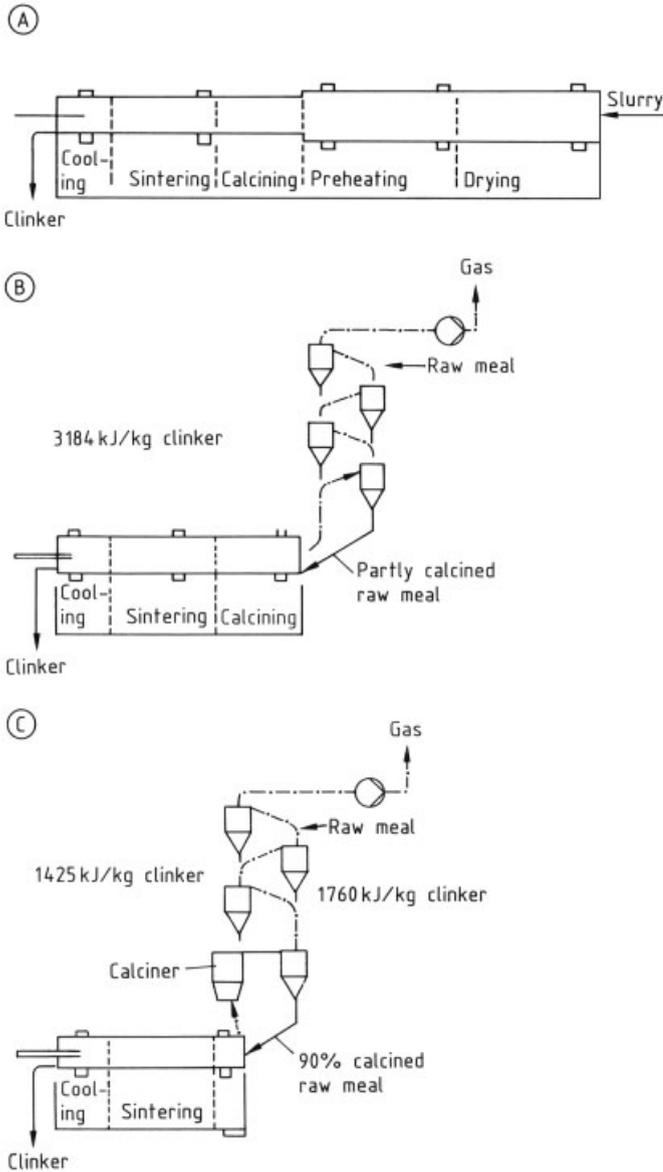


Figure 4. Kiln systems for cement clinker production of 2000 t/d [35]
 A) Wet process; B) Dry process; C) Process with precalcining

1.3.4. Iron Ore Reduction

The rotary kiln should continue to grow in importance as a reduction apparatus. It can employ a wide range of carbon carriers not suitable as reductants for shaft furnaces (e.g., the blast furnace): from anthracite and coke breeze to charcoal fines, lignite, and brown coal.

The charge (ore and reductant) usually moves through the rotary kiln countercurrent to the hot gases. Coupled reactions—ore reduction by carbon monoxide and reaction of carbon with carbon dioxide with regeneration of carbon monoxide—occur in the charge. The reactivity of carbon is critical for the process as a whole [39]. Some of the carbon monoxide formed es-

capacities from the charge so that oxidizing gases from the free kiln volume cannot permeate into it.

Reducing conditions depend on the temperature, reactivity, and quantity of the reductant; the residence time; and the charge holdup at the discharge end of the kiln. The rate of reduction can be controlled to meet a variety of objectives, from the formation of magnetite to the production of carburized molten pig iron. Details are sketched in Figure 5 and described briefly below.

In *magnetizing roasting*, the iron content of lean ore is transformed to magnetite (Fe_3O_4) at 700–1000 °C. The product is concentrated by grinding and magnetic separation. The temperature profile and reducing conditions can be controlled with gas- or oil-fired shell heaters located along the kiln; fuel is supplied to the rotating kiln through special seals. The reducing action can also be aided by the addition of small amounts of coal.

The most frequently used process for the production of sponge iron is the SL/RN process [40], [139], illustrated in Figure 6. Lump ore, pellets, titanomagnetite-containing sea-sand concentrates, zinc- and lead-containing residues from iron and steel production, and pellets from leach residues are reduced in existing plants (→ Iron, Chap. 2.6.4.).

1.3.5. Volatilization Processes

Metals and metal compounds with a high vapor pressure can be recovered by volatilization from their raw materials in a rotary kiln. The volatilization may be enhanced by selective reduction. Examples include arsenic, antimony, lead, cadmium, mercury, silver, tin, and zinc in elemental form or as compounds, for example, zinc as the metal and lead as PbS or PbCl_2 .

The way in which the charge moves through the rotary kiln (a rolling motion called “wälzen” in German) has given its name to the *Waelz process* used for decades in the volatilization of zinc (→ Zinc) and lead (→ Lead, Chap. 4.2.2.3.). Low-zinc ores and other raw materials are fed together with solid reductants to the kiln, where the metal is volatilized under reducing conditions. The vaporized metal is oxidized in the free volume above the charge and recovered as

dust (the so-called Waelz oxide) from the off-gas [41]. Figure 7 is a schematic of a modern Waelz plant. The Waelz process has also proved suitable for zinc- and lead-containing residues from iron and steel production [42]. A flow sheet of this process is shown in Figure 8. Higher productivity with less energy consumption and less mechanical dust formation can be achieved by pelletizing the feed. The Waelz kiln oxide can be purified by washing with Na_2CO_3 solution.

1.3.6. Other Applications

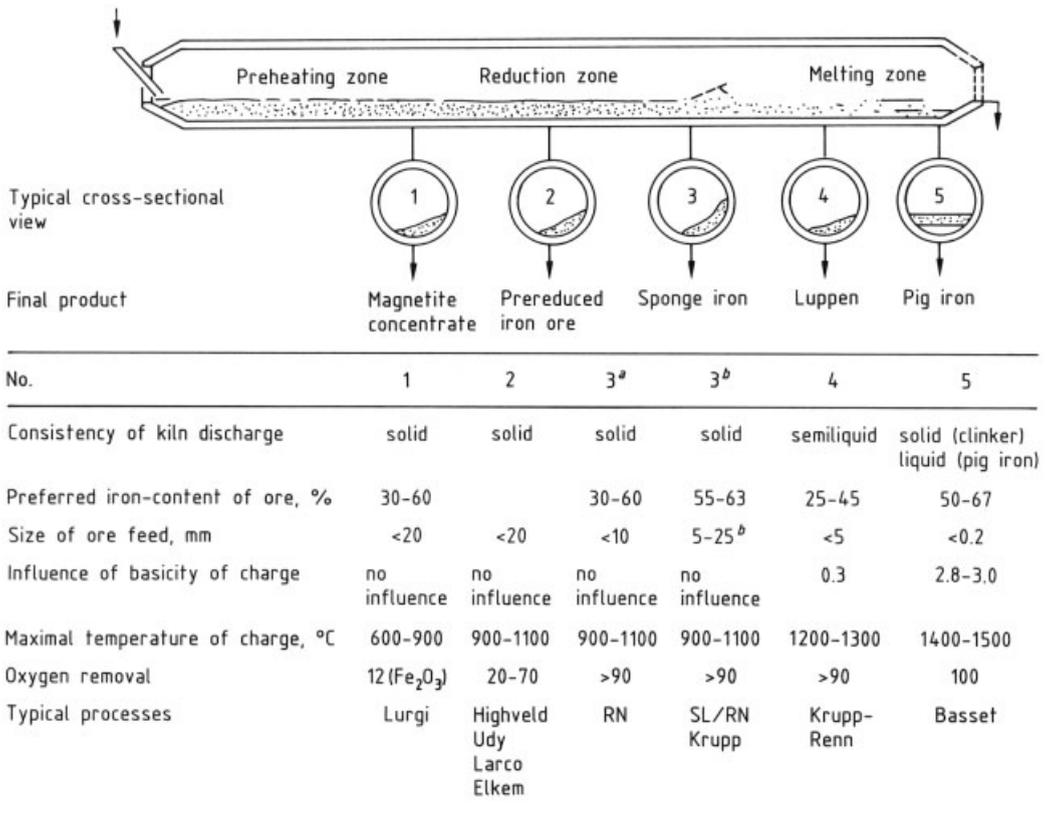
Other applications of the rotary kiln include:

- 1) Oxidation of ilmenite [43]
- 2) Calcination of pellets after preliminary heat treatment on a traveling grate (e.g., see → Iron, Chap. 2.1.1.5.)
- 3) Calcination of petroleum coke (→ Petroleum Coke, Chap. 3.2.) [44]
- 4) Reduction of heavy spar
- 5) Processing of gypsum to sulfuric acid and cement (gypsum – sulfuric acid process)
- 6) Production of TiO_2 pigment (→ Pigments, Inorganic, Chap. 2.1.3.1.)
- 7) Production of mercury (→ Mercury, Mercury Alloys, and Mercury Compounds, Chap. 4.1.3.)
- 8) Volatilization of zinc, lead, and copper with CaCl_2 [45]

Waste incineration and coal gasification may be important future applications of the rotary kiln.

2. Multiple-Hearth Furnaces

From a dominant position as a roasting furnace for sulfide ores (chiefly pyrites in sulfuric acid production), the multiple-hearth furnace has been almost completely displaced by fluidized-bed roasting equipment since the 1960s. Fluidized-bed devices (→ Fluidized-Bed Reactors) permit much higher throughputs than multiple-hearth furnaces, with substantially better control of reaction temperature and oxygen partial pressure in the roasting gas. Nonetheless, the multiple-hearth furnace will continue to find use in some special areas of process engineering.



^a % CaO/% SiO₂.

^b Ilmenites and iron sand: 0.05-0.5 mm.

Figure 5. Characteristics and possibilities for the reduction of iron ores in rotary kilns

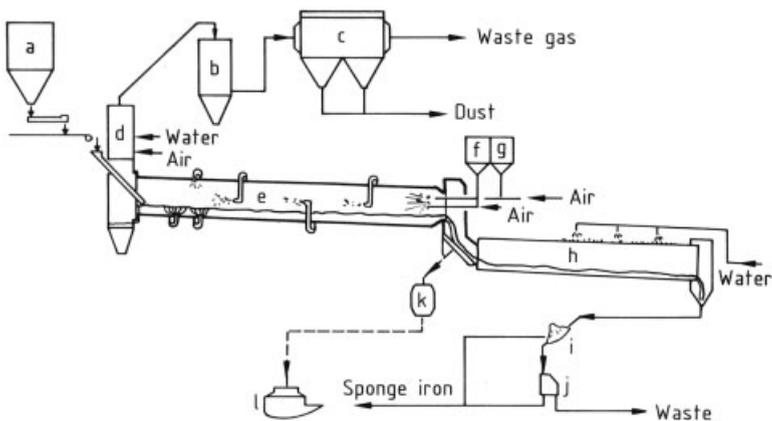


Figure 6. SL/RN process for sponge iron production

a) Bins for raw material; b) Waste-heat boiler; c) Aftercombustion chamber; d) Electrostatic precipitator; e) Rotary kiln; f) Coal bin; g) Fine-ore bin; h) Rotary cooler; i) Screening; j) Magnetic separation; k) Hot charging; l) Electric-arc furnace

The openings in the hearths, through which the charge travels from the top of the furnace to the bottom, therefore alternate from central to peripheral.

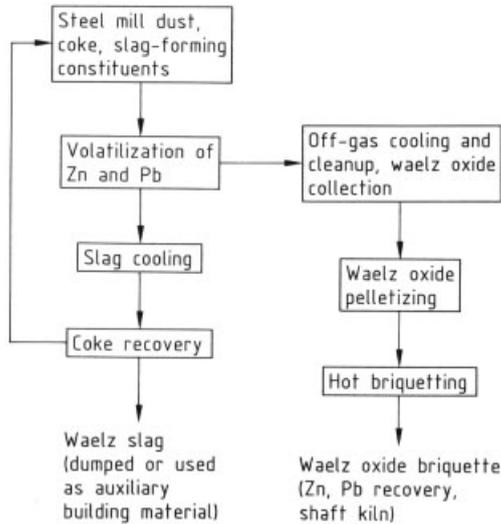


Figure 8. Flow sheet of Waelz process with steel mill dust as feed and briquetting of product

Because of the high temperature in the furnace, the shaft and rabble arms are air cooled. The shaft has double walls; cool air supplied by a fan enters the outside space, passes through the shaft and arms, and exits the furnace at 200–300 °C by way of the center space. Each hearth has several doors, which allow monitoring of the reaction and replacement of the rabble arms. The doors can be sealed tightly or can have adjustable air slots to admit cooling or combustion air if a slight subatmospheric pressure is maintained in the furnace.

Multiple-hearth furnaces are built in various sizing, ranging from 2 to 8 m in diameter and having 3–16 hearths. Residence time in the furnace is easily controlled by varying the shaft rotation speed or the number of rabble arms and teeth on each arm. Suitable reactions for the multiple-hearth furnace are

- 1) Slow reactions (because long residence times can be achieved in the multiple-hearth furnace)
- 2) Reactions between solids and quantities of gas that are too small to maintain a fluidized bed

- 3) Processes in which the solid is inlet in slurry form and the slowest and most gentle drying possible is desired
- 4) Processes in which solids must be exposed to a stepwise varying reaction temperature during thermal processing (within certain limits, the temperature and the gas atmosphere can be varied from hearth to hearth)
- 5) Reactions in which the solid undergoes slight softening, agglomeration, or sintering so that fluidized-bed processes cannot be employed

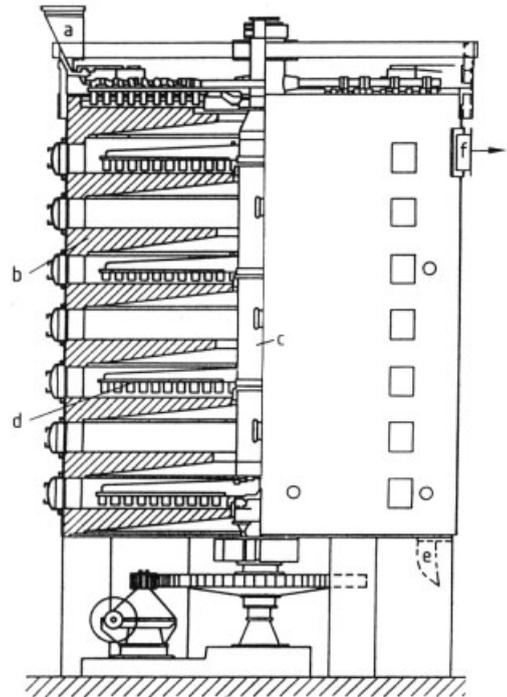


Figure 9. Lurgi multiple-hearth furnace [50]

a) Hopper; b) Circular hearth; c) Hollow shaft; d) Rabble arm with teeth; e) Discharge outlet; f) Gas outlet

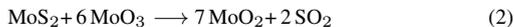
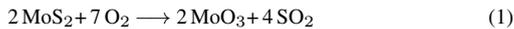
2.2. Applications

2.2.1. Roasting of Sulfide Ores

Since the development of fluidized-bed techniques, sulfide ores such as pyrite, pyrrotite, zinc blende, and chalcopyrite have not been roasted in multiple-hearth furnaces. Ores that can be roasted only with great difficulty, such as molybdenum disulfide, are still treated in multiple-hearth furnaces.

Because roasting reactions are exothermic, the furnace usually has to be heated only at the start of the process. The material fed to the top-most hearth is distributed by the teeth on the rabble arms, slowly transported to the center of the hearth, and dried. Then the ore falls into the first roasting zone, where it is heated in contact with hot roasting gas until it ignites. The reaction goes to completion as the charge is transported further over the hearths. On the last hearths, roasting air drawn or blown into the furnace from the bottom is preheated by cooling the residue. The progress of the reaction is monitored by measuring the temperature on the individual hearths.

The roasting of molybdenum disulfide (Eqs. 1–3) is carried out at ca. 630 °C (→ Molybdenum and Molybdenum Compounds, Chap. 4.2.). The hearths on which the exothermic roasting reactions (1) and (2) occur are cooled by the admission of air or water.



After the roasting reaction has gone largely to completion, the molybdenum dioxide product is oxidized to the trioxide (Eq. 3). This reaction, however, is not sufficiently exothermic to keep the temperature high enough to burn off the residual sulfur. In a furnace with a total of nine hearths, the seventh and eighth are therefore heated with oil or gas.

2.2.2. Use for Endothermic Reactions

For endothermic reactions such as the calcination of a magnesite, dolomite, bauxite, clay, or zinc carbonate, the heat required is delivered from outside into the furnace. If the feed materials can tolerate some overheating by flame radiation, one or more burners can be built into the furnace shell at the hearths where heating is required (see Fig. 10). Otherwise, hot flue gas is admitted at these locations after generation in one or more combustion chambers. Heat losses are higher and throughput capacities lower than those of fluidized-bed furnaces and rotary kilns, so the calcination reactions mentioned above are

rarely carried out in multiple-hearth furnaces. The use of this type of equipment is restricted to residues containing vanadium and tungsten.

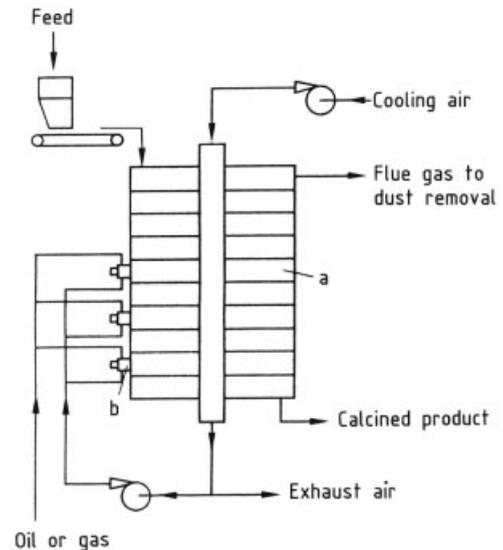


Figure 10. Heating of individual hearths with jacket burners [50]
a) Multiple-hearth furnace; b) Burner

Most *vanadium* is produced from vanadium-containing slags such as those from steelmaking. Because most of the vanadium in slag is in the tri- and tetravalent forms, which are insoluble in water, it must be converted to water-soluble pentavalent sodium vanadate by thermal oxidation and the addition of Na_2CO_3 and NaCl . This process is carried out in the multiple-hearth furnace (→ Vanadium and Vanadium Compounds).

The multiple-hearth furnace can also be used to oxidize *tungsten-containing slags* or residues from the metal fabrication industry (turning chips, grinding waste) in order to recycle the material in the form of WO_3 to tungsten production.

2.2.3. Clarifier Sludge Treatment

The flexibility of the multiple-hearth furnace led, in the 1980s, to its increasing use for the incineration of waste from a variety of sources. The main products treated by incineration are sludges from wastewater treatment and from cellulose and paper mills.

Today, most sludge incinerators built around multiple-hearth furnaces are designed so that combustion is self-sustaining, i.e., no fuel needs to be added. The sludge is therefore prepared by mechanical dewatering in centrifuges or filter presses.

If the degree of dewatering is insufficient for self-sustaining combustion, a thermal drying step is interposed. For sludge or waste incineration, the multiple-hearth furnace is equipped with an afterburning chamber (f) and gas vapor recycle (g) (see Fig. 11). The afterburning zone is needed for the residue-free combustion of volatile components at 800–900 °C. Recycling of vapors and flue gases by means of a fan thus helps by minimizing pollution and controlling temperature.

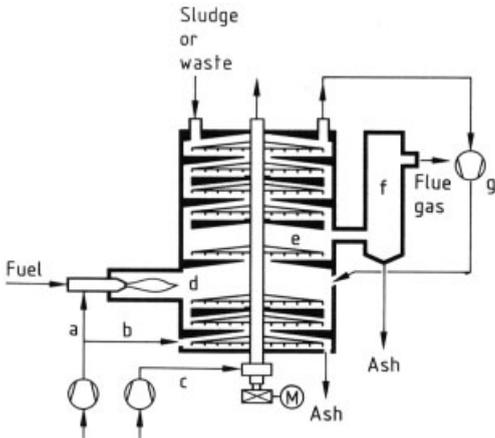


Figure 11. Multiple hearth for sludge incineration
a) Combustion air; b) Cooling air for ash; c) Cooling air; d) Startup burner; e) Multiple hearth; f) Afterburning chamber; g) Recycle fan

The use of multiple-hearth furnaces for sludge incineration led to the development of combined multiple-hearth–fluidized-bed (MHFB) furnaces in 1980. Furnaces of this type (Fig. 12) have the advantages of both the multiple-hearth furnace (slurry feed) and the fluidized-bed furnace for combustion processes.

In principle, such a device is a fluidized-bed furnace with a few hearths added on top as needed to predry the sludge. Flue gases ascending from the fluidized bed are drawn through the hearths in countercurrent to the slurry feed. About 50 % of the water is vaporized outside the fluidized bed, and the sludge is thus predried. Vapor produced by predrying can be recycled to

the burnup zone of the fluidized-bed. One advantage of this arrangement, compared to the conventional fluidized-bed furnace with slurry feed, is that the air excess can be reduced to 30–40 %, so neither supplemental fuel nor external predrying is usually necessary (given an appropriate degree of dewatering).

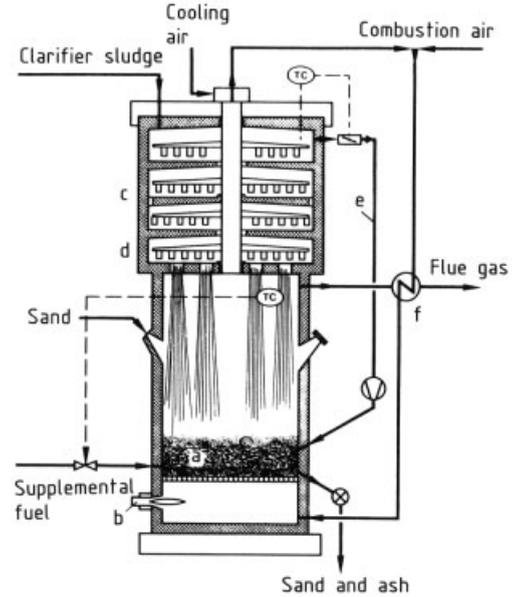


Figure 12. Combined multiple-hearth–fluidized-bed furnace (MHFB)

a) Fluidized bed; b) Startup burner; c) Drying hearths; d) Distribution hearths; e) Gas–vapor recycle; f) Preheater

3. Shaft Furnaces

The shaft furnaces have a variety of uses in metallurgy. The *Rchette furnace* is employed in lead production (→ Lead, Chap. 4.2.2.2.). Figure 13 shows a chair jacket profile used today. The distinguishing feature of the lead blast furnace is that the throat widens upward. The products, lead bullion and slag, are obtained by reduction; the slag contains any zinc present as ZnO. The *Imperial Smelting furnace* (Fig. 14) was developed for the simultaneous processing of lead and zinc concentrates (→ Zinc). It differs from ordinary lead blast furnaces by having a hot stack and a zinc splash condenser.

In the following, the *iron blast furnace* (→ Iron, Chap. 2.5.) is described in more detail as it is the most important type of shaft fur-

nace. The blast furnace has the form of two truncated cones set with their large bases together. The widening of the stack from top to bottom reduces the frictional resistance as the burden moves downward.

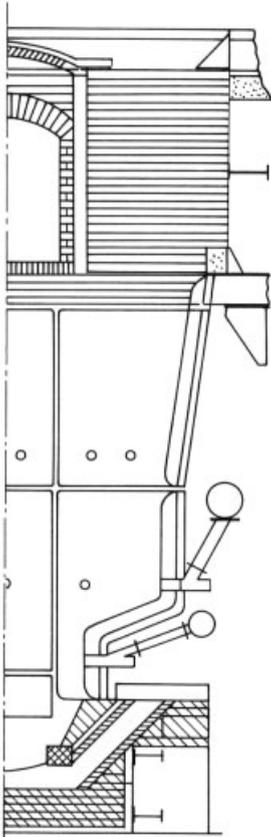


Figure 13. Profile of a lead blast furnace

A typical iron blast furnace is shown in Figure 15. Modern blast furnaces have a hearth diameter of 10–14 m, a volume of 2000–4000 m³, reach throat gas pressures of up to 0.35 MPa, and have production capacities of $(1.5 - 3.5) \times 10^6$ t/a of pig iron. The blast furnace is divided into the following sections: throat, stack, bosh, and hearth.

The blast furnace is charged with burden, coke, and additives via the charging platform (throat). The blast-furnace gas or top gas is also withdrawn from the furnace through the throat. For design reasons, the throat diameter should be kept as small as possible. The *stack* is conical and terminates in the throat at the top. It expands downward to the *belly*. The next section

down is the *bosh*, which narrows toward the bottom and forms the transition to the *blast-furnace hearth*. The narrowing of the bosh corresponds to the decrease in burden volume as the coke is consumed. This cylindrical section has water-cooled *tuyeres* through which the blast is introduced into the furnace. The hearth should have a relatively small diameter because the hot blast does not have a long penetration depth and otherwise would not reach the interior of the burden. The two main products of the furnace, slag and iron, collect in the hearth. Excess slag is withdrawn through slag holes, while the hot metal which has a higher density, is withdrawn through tap holes.

The main function of the iron blast furnace is to reduce iron oxides to metallic iron. The reducing melting of iron-containing substances takes place in a countercurrent arrangement; the ascending hot gas from coke combustion heats and reduces the descending burden.

The dimensions of a modern “high-top-pressure” blast furnace are as follows

Hearth diameter	11.5 m
Belly diameter	12.6 m
Throat diameter	8.4 m
Total hearth height	6.23 m
Distance from stool to tap hole	2.38 m
Distance from tap hole to slag hole	2.05 m
Distance from tap hole to tuyere level	3.25 m
Bosh height	3.30 m
Belly height	2.30 m
Shaft height	18.35 m
Throat height	2.75 m
Usable capacity (from tuyere level to 1 m below large bell in let-down position)	2.353 m ³
Total capacity	2.820 m ³
Diameter of large bell	6.10 m
Diameter of small bell	2.20 m
Number of tuyeres	28
Number of tap holes	3
Number of cooling plates in tuyere level and bosh	476
Number of stack cooling boxes	800

The throat of this modern blast furnace is closed by a dual-chamber structure consisting of a lower bell, a small bell, and four clack valves. The furnace consists of a fully armored steel structure: a multistory frame built on a square-plan portal frame. The furnace frame accepts the loads from the furnace top, the four gas offtake pipes, the over-throat construction, the bustle

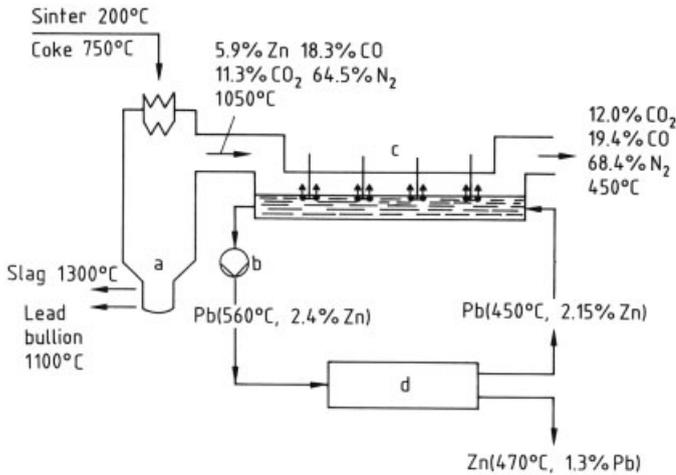


Figure 14. Imperial Smelting blast furnace with zinc condensation by molten lead [50]
a) Blast furnace; b) Pump; c) Spray condenser; d) Cooling system

pipe, and the working platforms. Compensators take care of length changes: one compensator is located between the upper furnace and the furnace end; three articulated compensators are located in each of the four gas offtake pipes. This blast furnace is designed for the production of 6500 t/d of pig iron [46–48].

Furthermore, metallurgy shaft furnaces are used for

- 1) Anode copper refining (→ Copper, Chap. 6.1.)
- 2) Pure copper melting in cast shops in ASARCO shaft furnaces (→ Copper, Chap. 6.3.)
- 3) Recovery of copper from secondary materials (→ Copper, Chap. 5.9.)
- 4) Cast iron melting in Cupola furnaces (→ Steel, Chap. 3.5.5.2.).

For shaft furnaces, ores, concentrates, or metals must be lumpy or be agglomerated by sintering, pelletizing, or briquetting. To some extent, fine ores or secondaries can be blown through the tuyeres directly into the raceway for very fast reduction.

4. Smelting, Melting, and Refining in Bath and Flash Smelting Reactors

Fine concentrates or secondaries can be smelted without agglomeration in flash (after drying) or

bath smelting furnaces. The heat of exothermic chemical reactions provides the energy for auto-genous smelting. All these furnaces are operated continuously.

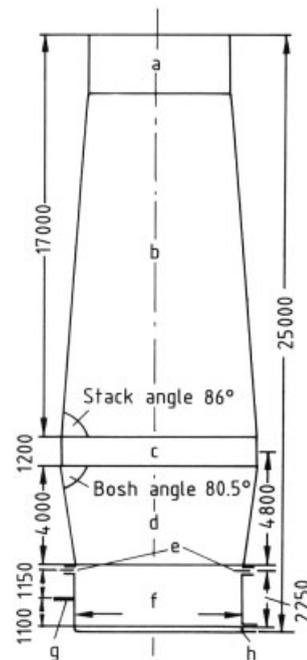


Figure 15. Schematic of a typical iron blast furnace with common heights (in mm) and angles
a) Charging platform (throat); b) Stack; c) Belly; d) Bosh; e) Tuyeres; f) Hearth; g) Slag hole; h) Tap hole

A wide variety of such smelting furnaces and converters are used in metallurgy. These smelting furnaces represent a modern approach of intensive metal smelting under environmentally “clean” conditions.

4.1. Bath Smelting Furnaces

In bath smelting furnaces and converters oxygen or oxygen-enriched air is blown into molten metal or matte baths via tuyeres (Fe, Cu), lances (Fe, Ni, Pb) or injectors (Fe) to oxidize elements that are to be removed as impurities. Coal or reducing gases may also be blown into molten slags via tuyeres, lances, and injectors for slag reduction (Pb). In the case of aluminum, chlorine is blown through pipes and stirrers into the molten metal bath to remove alkaline and alkaline-earth elements.

Bath smelting furnaces have been described in detail in the Encyclopedia and elsewhere [107], [140–148]. They are already in use for the production of copper by the Mitsubishi (→ Copper, Chap. 5.7.2.) and Isasmelt/Ausmelt (→ Copper, Chap. 5.4.4.) processes; the production of copper matte from concentrates and secondary materials in the Noranda (→ Copper, Chap. 5.7.1.), CMT/Teniente (→ Copper, Chap. 5.4.6.), and Vanyukov (→ Copper) processes; and for the production of lead bullion following the QSL and Isasmelt technologies from concentrates and secondary materials (→ Lead, Chap. 4.4.3.). Bath smelting furnaces are in development for the direct steel production from iron ores (→ Iron, Chap. 2.7.2., → Iron, Chap. 2.7.3.).

4.2. Flash Smelting Furnaces

In 1949 the first Outokumpu flash smelter started operation. By now 36 Outokumpu flash smelters treat copper concentrates, and six smelt nickel concentrates; 50 % of the global primary copper and 30 % of the nickel are flash smelted in Outokumpu-licensed plants. In addition, four Inco flash smelters and three Kivcet furnaces are in operation.

The Outokumpu furnaces consist of

- A circular reaction shaft (7–9 m high, 6–7 m in diameter) for roasting and smelt-

ing of dry concentrates in suspension with highly enriched air

- A settling hearth with an area of 120–160 m² for collection of the droplets and separation of matte (metal) and slag
- An off-take shaft for waste gas and flue dust.

More details are given in the Encyclopedia (→ Copper, Chap. 5.5.1., → Nickel, Chap. 4.2.1., → Lead) and elsewhere [107], [108], [141–144], [149].

4.3. Bath Melting and Refining

Bath melting and refining furnaces are often used for melting, refining, and alloying metals. The furnace size ranges from 1 t to several hundred tons. These furnaces are operated batchwise and are fed with solid and liquid metal. They are of the stationary, tilting, or rotary type.

Their applications include:

- 1) Electric arc furnaces and induction furnaces for steel and cast iron melting and refining (→ Steel, Chap. 3.5.5.2.)
- 2) Stationary and tilting hearth furnaces and rotary for aluminum melting, refining, and alloying
- 3) Stationary hearth furnaces for copper matte and ferronickel smelting
- 4) Rotary furnaces for anode copper melting and refining
- 5) Stationary and tilting hearth furnaces for copper scrap melting and refining
- 6) Rotary furnaces for secondary lead smelting

An example of a gas-heated aluminum rotary furnace for melting and refining of Al scrap is shown in Figure 16 [150].

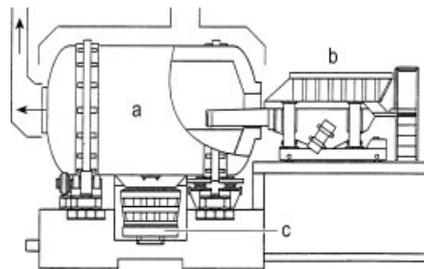


Figure 16. Conventional rotary furnace for melting Al scrap a) Rotary furnace; b) Loading machine; c) Salt slag bucket



Figure 17. 100-t-steel melting direct-current arc furnaces, type UNARC (courtesy of MAN GHH).

Figure 17 shows two modern gas-heated tiltable aluminum melting and casting furnaces. For mixing the melt, such furnaces are stirred mechanically, inductively, or by gas.

4.4. Converters

Converters are mainly used for

- 1) Conversion of pig iron together with scrap into steel (\rightarrow Steel)
- 2) Conversion of copper matte into blister copper (\rightarrow Copper, Chap. 5.6.) and the refining of secondary black copper (\rightarrow Copper, Chap. 5.9.)
- 3) Refining of secondary aluminum
- 4) Conversion of nickel matte into nickel (\rightarrow Nickel, Chap. 4.2.2.) and lead matte (\rightarrow Lead, Chap. 4.4.2.2.)

Copper is up to now the only metal continuously converted from matte to blister copper on an industrial scale in several plants [140–144], [149], [151] (\rightarrow Copper, Chap. 5.7.).

The Mitsubishi converter has been operated for more than 30 years on liquid matte feed with lance blowing [140–144], [151]; the Noranda converter is a newer development [141], [151] and is operated with tuyeres.

Another development is flash converting of ground copper matte to liquid blister copper with oxygen. The first industrial plant started operation a few years ago in the United States. A second plant, in Peru, will follow soon [132], [140], [141], [151].

The main converting operation is steelmaking with ca. 450×10^6 t/a in 1996. Converters reach sizes of up to 400 t per batch, with annual capacities of up to 4×10^6 t. Molten iron together with steel scrap (for cooling) is transformed to steel in the converter. Accompanying elements, particularly carbon, are oxidized to a desired level by oxygen.

In the past, air was used for converting in the Bessemer (since 1855) and Thomas (since 1877) converters. Nowadays only oxygen converters are in use (Fig. 18) which employ lances for top blowing (e.g., LD, LD-AC, Kaldo) and injectors for bottom blowing [e.g., OBM, Q-BOP] or side blowing (AOD). See also \rightarrow Steel).

The *LD process* (see Fig. 18 A) was developed in 1952 in Linz and Donawitz, Austria. Oxygen is blown onto the bath of molten pig iron from above through a water-cooled oxygen lance. The LD process can handle pig iron containing up to 0.5 % phosphorus. The *LD-AC variant* (A for Arbed, Luxembourg; C for CNRM, Liège, Belgium, Fig. 18 B) has been developed for high-phosphorus iron. Multiple

slagging makes it possible to dephosphorize the melt.

The *Bottom-Blown Oxygen Process (BOP)* is called the OBM (Oxygen-Bottom-Maxhütte) process in Europe (Fig. 18 C), and is generally used with high-phosphorus pig iron. In the United States and Japan it is called the Q-BOP process and is used with low-phosphorus pig iron. In the bottom-blown converter developed in 1968, oxygen is admitted from below to the reaction space through a number of tuyeres (5 to 15). The oxygen jet is surrounded by a protective medium containing hydrocarbons, which serves to cool the tuyeres. The bottom-blown process features short blowing times and low iron losses.

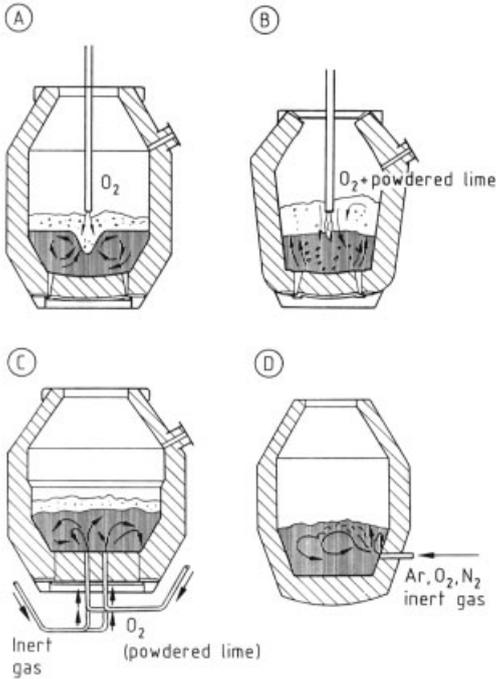


Figure 18. Different types of converters
A) LD converter (BOF); B) LD-AC converter; C) OBM converter; D) AOD converter [131].

The *AOD (Argon-Oxygen-Decarburization) converter* (Fig. 18 D) permits oxidation and degassing of steel before casting. Figure 19 shows working positions of a converter. Loading always takes place through the mouth of the converter. Steel is tapped via a taphole situated in the upper side by tilting the converter.

A modern development of melting and converting of scrap is the *energy-optimizing furnace (EOF)* which combines preheating, melting, side blowing, and direct heat recovery from the reactor gases [52]. Plants with batch weights of 30–100 t have been built. For the 30 t reactor in Pains, Brazil some consumption and performance figures (per tonne of molten steel from 100 % scrap) can be given [154]:

Oil	3–5 kg
Coke	85–100 kg
O ₂	110–135 m ³ (STP)
Tap-to-tap time	65 min
Blowing time	40–50 min
Tap temperature	1680 °C
Refractory consumption	6 kg

5. Electrothermal Reactors

5.1. Introduction

5.1.1. History [54–62]

The use of electricity for metallurgical applications started in at the beginning of the nineteenth century. As early as 1810, DAVY performed experiments in which he produced alkali metals via *fused salt electrolysis*. In 1888 HÉROULT patented a small electric furnace for the production of aluminum, which formed the basis of the present-day electrolytic recovery of aluminum from alumina [54]. The use of *induction* as a heating method was patented by DE FERRANTI in 1887 [54]. Although the experimental use of an electric arc can be traced back to 1810, the development of the first *electric arc furnace* is attributed to SIEMENS, who developed a small arc furnace in 1878–1879 [54]. From this humble beginning, the use of an arc for melting and smelting in furnaces progressed from an arc furnace (developed by HÉROULT in 1900) to the ultrahigh power (UHP) technology (developed in 1960–1962) [55], [56], with which very high melting rates can be attained.

The earliest recorded application of *electroslag* refining appears in a book by SLAVYANOV published in 1892 [57], but reported work performed in the United States could be dated 20 years earlier. By the time of HOPKINS' development of the electroslag process in 1935, consumable vacuum arc refining was making great headway in the United States [57].

Vacuum melting

Converter tilting positions

Hot metal charging

Scrap charging

Tapping · Slag pouring · Sampling

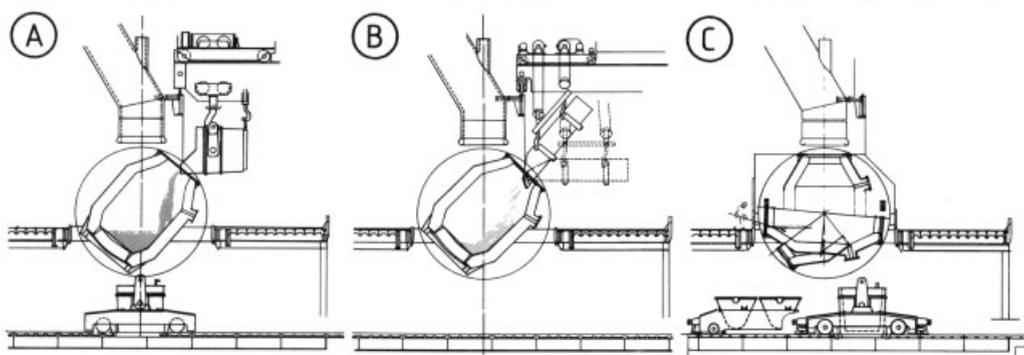


Figure 19. Working positions of a converter [131]

was introduced as a plant-scale operation in 1917 when ROHN melted nickel-base alloys by resistance heating. In 1923, Heraeus Vacuum-schmelze (Hanau) was founded that operated vacuum induction furnaces; by about 1956 the potential of vacuum arc remelting for steels, as well as nickel- and titanium-base alloys had been exploited for the production of improved gas turbine disks, shafts, and casings [58].

The use of electron-beam technology for smelting and melting is as young as plasma metallurgy, although experiments with electron beams (at the time known as cathode rays) commenced as early as 1852 [59]. The conceptual birth of this technology is attributed to VON PIRANI, who patented his ideas in 1907. No further significant developments occurred until semi-continuous electron-beam melting was first performed in a cold mold crucible by SMITH and coworkers in 1954, who attempted to consolidate titanium powder [59]. By 1957 facilities were available for processing titanium ingot 80 mm in diameter and 1.5 m in length.

Plasma metallurgy was merely a topic of science fiction up to the 1950s [60]. The first investigations into carbothermic reduction of oxides were carried out in the late 1950s [61]. In a 1962 publication the use of plasma torches for melting scrap was traced back to the Linde Company, a division of Union Carbide [62].

5.1.2. Electrothermal Furnaces [55–89]

The short historical overview shows that most of the basic principles of electrothermal furnaces have been known for a considerable time. Electrothermal furnaces are classified on the basis of these principles as follows:

Resistance Furnaces. In these furnaces heat transfer occurs either directly or indirectly according to Ohm's and Joule's laws. They can be operated in an a.c. or d.c. mode.

Applications: Furnaces which implement *direct resistance* include:

- 1) Resistance furnaces for solid-state reactions, e.g., production of graphite and carbides [63].
- 2) Resistance furnaces for the production of copper, nickel, iron, tin, and zinc or their intermediate products from oxidic and sulfidic materials and slags [64–73].
- 3) Electroslag refining (ESR) for the production of clean ferrous or nonferrous metals and alloys such as titanium, steels, and superalloys, [57], [73], [154].
- 4) Furnaces that employ a combination of arc and resistance heating are used for the production of calcium carbide, ferroalloys, pig iron, phosphorus, and silicon compounds by reduction. Electrodes are situated within the charge; reduction and melting occur within the high-temperature zone around the electrodes [74], [75].

- 5) Fused-salt electrolysis cells for the production of aluminum and alkali metals may also be considered to be electrochemical thermal reactors [76], [77].
- 6) Salt-bath furnaces for the heat treatment of metals.

Indirect heating is mostly performed in a closed chamber in which heating elements, situated in the walls or suspended in the chamber, transfer their heat via radiation, conduction, and convection to the object to be heated. This type of furnace is applied for heat treatment of metals, ceramics, and for the production of carbides [55], [56], [78]. These types of furnaces are not discussed in this article.

Arc Furnaces. In arc furnaces the heating occurs because of the high temperature ($> 6000\text{ }^{\circ}\text{C}$) of a gas plasma created by the arc. These furnaces may be operated either in an a.c. or d.c. mode.

Applications:

- 1) Steel scrap and cast iron scrap (in the past also copper scrap) are melted in arc furnaces in which the arc is situated above the molten slag. The slag acts as a heat distributor and a refining agent for the molten metal [154].
- 2) In vacuum arc remelting (VAR) a consumable electrode, made from the metal to be melted/refined, is melted in a vacuum to produce high-purity metals. An example is the production of high-purity titanium from titanium sponge [58], [79], [154].

Induction Furnaces. In induction furnaces the heat is generated according to Lenz's, Ohm's, and Joule's laws. Two types of furnaces are generally used for melting operations the *crucible furnace* and the *channel furnace* [80], [81], [94], [95], [154].

Applications:

- 1) *Crucible furnaces* are used mainly to melt particulate cast iron, (stainless) steel, base metals, copper, and aluminum.
- 2) *Channel furnaces* are applied in the ferrous industry as a holding furnace. In the nonferrous industry they are also used as a melting furnace for aluminum, zinc, and copper.
- 3) In *vacuum induction furnaces* volatile components are removed from less volatile metals and alloys. Examples are the refining of

special steels, superalloys, and copper. Silver crusts from lead refining are also enriched in silver by volatilization of zinc.

Induction heating is also used during annealing, hardening (\rightarrow Steel), brazing, soldering (\rightarrow Soldering and Brazing), and longitudinal welding (\rightarrow Welding and Cutting).

Electron-Beam Furnaces. In electron-beam furnaces electron guns produce high-energy electrons, which impart their energy to the furnace charge to affect its melting [58], [59], [155], [156].

Applications. Electron-beam furnaces are used to melt and/or refine refractory metals such as vanadium, niobium, and tantalum; metals such as molybdenum and tungsten; reactive metals such as zirconium and hafnium; and ceramics such as zirconia, alumina, and uranium carbide.

Plasma Furnaces. In these furnaces heating is performed by either transferred or nontransferred arc plasma torches (\rightarrow Plasma Reactions). In contrast to arc furnaces, where arcs are produced between a graphite electrode and the charge, plasma furnaces use gas-stabilized plasma arcs produced by water-cooled plasma torches with nonconsumable electrodes. Consumable hollow carbon electrodes have also been applied [60–62], [82], [83].

Applications. Plasma furnaces have been employed commercially, e.g., to produce ferrochromium, to melt steel scrap, and to recover valuable metals from steel flue dust [125].

Laser Heating. Although "laser furnaces" are nonexistent, many applications of laser heating have been reported in metallurgy, e.g., in cutting, welding, machining, and surface treatment of metals [55], [56].

Miscellaneous Types of Heating. In addition to the heating methods discussed above, infrared, dielectric, and microwave heating are also available. As these are not presently used to effect a chemical reaction at high temperature on an industrial scale, they fall outside the scope of this article.

Table 1. Recovery of metals in selected electrothermal furnaces as a function of the type of reduction, reductant, and heating method

Metal	Type of reduction	Reductant	Type of heating
Aluminum/magnesium	fused-salt electrolysis	electrochemical	resistance
Copper/nickel	matte smelting		resistance
Ferroalloys (Cr, Mn, Si, Ni)	carbo-/silicothermal	C/SiMe	resistance
Flue dusts (Zn, Pb)	carbothermal	C	plasma, resistance
Magnesium	silicothermal	FeSi	resistance
Scrap/reduced iron pellets (Fe)		C	arc
Slags (Cu, PbZn)	slag smelting	C	resistance
Phosphorus, CaSi ₂ , Ca ₂ C	carbothermal	C/Ca ₂ C	resistance arc

Table 2. Metal refining operations

Metal	Type of furnace	Type of heating	Removed impurities
Steel	arc furnace	arc	C, O, and diverse impurities
Steel	electroslag	resistance	inclusions
Ti, Zr	vacuum arc	arc	H, Mg, Cl
V, Nb, Ta, Hf, Zr	electron beam	electrons	C, O, N, H, and diverse impurities
Superalloys, special steels	vacuum induction	induction	C, O, N, H, and diverse impurities

Table 3. Advantages and disadvantages of electrothermal furnaces

Specific property	AF ^a	RF ^b	IF ^c	ESR ^d	VAF ^e	VIF ^f	EBF ^g
High power density	+	+	+			+	+
Very high temperature	+	+					+
Very good heat transfer		+	+	+		+	
Good mixing		+	+			+	
Water-cooled inert crucible				+	+		+
Controlled atmosphere	+	+	+	+	+	+	+
Very low p_{O_2}			+		+	+	+
Low off-gas volume	+	+	+	+	+	+	+
High specific energy consumption				+			+
Low smelting rate				+			+

^a AF = arc furnace^b RF = reduction furnace^c IF = induction furnace^d ESR = electroslag refining^e VAF = vacuum arc furnace^f VIF = vacuum induction furnace^g EBF = electron-beam furnace

Fields of Applications of Electrothermal Furnaces. A number of applications have already been given [78], [84–89] and further general information on electrothermal furnaces may be obtained from [93–96]. Electrothermal furnaces may be used for the *production of metals from raw materials by reduction*. Table 1 gives a summary of the applications of the above-mentioned techniques according to the metals produced.

Electrothermal furnaces may also be applied during metal refining. A summary of selected furnace types and their application during the *refining of specific metals* is presented in Table 2. The removed impurities are also given.

If cheap electrical energy is available heating in electrothermal furnaces has many advantages over heating with fossil fuels (Table 3).

Specific advantages associated with particular furnaces used to remelt certain metals are summarized in Table 4.

5.1.3. Energy Consumption and Production Capacities

Typical energy consumption for the production of various metals and alloys are given in Table 5 as a function of the type of furnace. The total energy consumption is a very important parameter for optimization for economic reasons. Elec-

trothermal reactors are also applied to produce nickel and ferronickel. Table 6 gives the energy consumptions for various ore compositions. The large content of platinum group metals (PGMs) in the ore of the Rustenburg operation in South Africa makes this process economically viable despite its high energy consumption.

Table 4. Remelting of metals and the advantages of specific furnaces

Metal	Type of furnace	Reason for application
Steel	arc	high melting capacity
Steel, cast iron, Al alloys, Cu alloys, Zn	induction	control of the atmosphere and the alloy composition
Ti, Zr	vacuum arc	no crucible and gas reactions

5.1.4. Economic Aspects

World production and energy consumption data for the production of metals, alloys, and special

metals in electrothermal furnaces are summarized in Tables 7 and 8.

5.2. Resistance Furnaces

5.2.1. Basic Principles [55], [56], [67]

All resistance furnaces operate on the basis of Joule's law, i.e., an electrical conductor emits heat when a current flows through it. The quantity of electric power that is converted into heat may be expressed by:

$$P=UI \quad (\text{Joule's law}) \quad (1)$$

where P is the electric power (W), U the voltage (V), and I the current (A).

Ohm's law relates the resistance of the conductor (R in Ω) and the current through it to the applied voltage:

$$U=RI \quad (\text{Ohm's law}) \quad (2)$$

Substituting Equation (2) into Equation (1) gives

Table 5. Process data for smelting and melting processes

Type of furnace	Metal	Crucible capacity, t	Furnace power, MW	Throughput, t/h	Energy consumption, kW · h/t
Induction	Al	1–40	0.3–4	1–8	500
	Cu	5–25	1–3	3–7	400
	cast iron	0.08–60	up to 17	0.5–32	520
	steel	0.08–60	up to 17	0.2–30	650
Vacuum induction	NiCo	1–10	1–2	0.4	1200
	Cu	3–10		1.5	400
Electroslag refining	steel	2–160	1.5	0.5–1.5	1300
	NiCo	< 5		0.3	900
Electron beam	Nb, Ta	0.5–2	< 1.2	0.02–0.4	6000–15 000
	Mo, W			0.02–0.1	< 5000
	Ti, NiCo		≤ 5	0.2–1.0	1000
Vacuum arc	steel, Ni	50			
	Ti	10			
	Mo, Nb, Ta		0.3–3		

Table 6. Process data for the production of nickel/ferronickel from sulfidic and oxidic ores in resistance furnaces

Nickel concentrate	Ore body	Ore composition, %			Energy consumption	
		Ni	Cu	Co	kW · h/t ore	MW · h/t Ni + Cu
Sulfide ore	Manitoba	10.5	0.4	0.2	430	5.5
	Rustenburg (≤ 30 ppm PGM) *	3.5	2.0	0.1	500	9.5
	Cerro Matoso	3.0			450	16.0
Oxide ore	Larymna	1.2			420	35.0

* PGM = platinum group metals

Table 7. World production and energy consumption data for the production of metals and alloys in electrothermal furnaces

Metal	Production		Size of furnace	Energy consumption, MW · h/t
	10 ³ t/a	Year		
Aluminum	22 600	1998	≤ 300 kA	14
Calcium carbide	6400	1982	60 MW	3
Calcium silicide	100	1980	30 MW	12
Chromium	10	1980		
Electrosteel	244 000	1996	100 MW	0.5 – 0.6
Ferrosilicon	2900	1980	40 – 150 MW	
Carburé				4
Affiné				8
Ferromanganese	4600	1980	30 MW	
Carburé				3
Affiné				1.5 – 2.0 + SiMn
Suraffiné				1.8 – 2.5 + SiMn
Ferromanganese	30	1998		
Ferrosilicon	3300	1978		≤ 50 MW
FeSi 45				5
FeSi 75				9
FeSi 90				13
FeSi 98				14.5
Magnesium				
Fused-salt electrolysis	290	1998	100 kA	14
Silicothermal	84	1998	6 MW	11 + FeSi 75
Manganese	100	1980	20 – 60 MW	
Nickel from sulfide	800	1998	20 – 30 MVA	see Table 6
Nickel from oxide	205	1998	45 – 60 MVA	see Table 6
Phosphorus	1300	1977	≤ 70 MW	13
Silicon	500	1980		
Silicochromium	365	1980		7
Silicomanganese	1700	1980	20 – 60 MW	3.7 – 6

$$P = RI^2$$

The amount of energy (heat produced in Joules after t seconds) may be represented by:

$$Q = Pt = RI^2t$$

The above equations show that the higher the resistance of a conductor or the larger the current, the more electric energy is converted into heat. The resistance of a conductor depends on the resistivity of the material and on its shape (length and cross-section):

$$R = \sigma l / S$$

where σ is the resistivity ($\Omega \cdot \text{cm}$), l the length, and S the cross-section.

The resistivity is also a function of the temperature:

$$\sigma_T = \sigma_{273\text{K}} (1 + \alpha T)$$

where σ_T is the resistivity at T Kelvin, $\sigma_{273\text{K}}$ the resistivity at 273 K, T the temperature in K,

and α the resistivity temperature coefficient in K^{-1} .

In most cases slag acts as the main resistance in furnaces. The resistivities for typical metallurgical slag materials are presented in Table 9.

Table 8. Annual world production of special metals

Metal	Production, 10^3 t/a	Year
Vanadium	0.1	1992
Niobium	1.4	1985
Tantalum	1.2	1984
	0.65	1985
Titanium	90	1984
Zirconium	6	1982
	8	1983
Hafnium	0.1	
	0.25	1983

Table 9. Resistivities of slag materials [65]

Compound	Temperature, $^{\circ}C$	Resistivity, $\Omega \cdot cm$
Ferrous/nonferrous slags		
$CaSiO_3$	1550	3.85
Ca_2SiO_4	1550	3.13
$FeSiO_3$	1400	0.83
Fe_2SiO_4	1400	0.20
FeO	1400	0.004
Al electrolyte		
Na_3AlF_6	1000	0.45
Na_3AlF_6	1100	0.42
Ti slags		
70 % TiO_2	1800	0.033
80 % TiO_2	1800	0.020
90 % TiO_2	1800	0.009

Direct resistance furnaces exploit the above principles for metallurgical purposes (see page 17). Indirect resistance furnaces fall outside the scope of this article and are not discussed here.

In direct resistance furnaces the feed or charge is the conductor and its resistance to the current flowing through it creates the heat for melting. The current in these reactors flows between at least two or more electrodes, one of which may be submerged in the material to be heated/melted. Direct resistance furnaces may be divided into three categories on the basis of the reactions taking place in them:

- 1) Reduction resistance furnaces
- 2) Refining resistance furnaces
- 3) Solid state resistance furnaces

5.2.2. Reduction Resistance Furnaces [97–108]

Electrothermal reduction furnaces use electric energy to heat the feed to the required operating temperature. In conventional reduction furnaces, heat liberated during the exothermic reaction between, for example, coke and oxygen is utilized to heat the feed. In electrothermal furnaces, coke is only needed for reduction.

Reduction resistance furnaces have a number of advantages over furnaces using fossil fuels:

- 1) Electrothermal processes permit higher productivities due to higher temperatures and energy densities
- 2) Higher grade products can be produced because ash and impurities (e.g., phosphorus and sulfur) derived from the fossil fuel are absent
- 3) Since the reactors are usually covered, dross formation can be minimized because atmospheric oxygen may be excluded
- 4) A smaller volume of off-gas volume is produced by resistance reactors with a higher carbon monoxide concentration because only reduction reactions take place
- 5) Electric furnaces can easily be enclosed, permitting tight control of the off-gas composition
- 6) Metallurgical coke can be replaced by, for example, charcoal which contains much less impurities
- 7) If the furnace is operated under vacuum conditions, reduction and degassing can take place in a single step

An obvious disadvantage of electrothermal furnaces are high energy costs that result from their energy-intensive operation. However, in countries where hydropower or inexpensive or excess electric power is available, this is an economically viable method for producing metals.

5.2.2.1. Furnace Construction and Operating Parameters [55], [56], [65], [84]

Normally two molten phases are present in a reduction furnace: a salt or oxide slag floats on the second phase (the produced metal or matte) that collects at the bottom of the furnace. Small

amounts of solid feed are added continuously. This open-bath operation can be used for the production of FeSi, Si, CaSi, and Ti slags, for example. The electric power is usually transferred to the furnace by three or six electrodes that are submerged in the molten slag. For the production of ferroalloys electrode diameters are 0.1–1.0 m and current densities are 5–15 A/cm², whereas for matte smelting the electrode diameters lie between 0.6 and 1.4 m and current densities between 2 and 3 A/cm². Typically, three-phase current circuits are used. The electric resistance of the slag produces heat which keeps the molten phases in a liquid state and supports the reduction reactions.

In some cases large amount of solids (e.g., the feed) can float on top of the slag (covered-bath operation for the production of FeCr, FeMn, SiMn, FeNi, CaC₂). In addition to resistance heating, these solids are also heated by electric arcs (see Section 5.3) which are created between the feed and the electrodes, and between the individual feed grains. Hence, these furnaces may also be called submerged-arc or arc-resistance furnaces. However, since no clear classification between this type of furnace operation and a pure resistance furnace can be made, they are discussed in this section.

The *electrodes* used in reduction resistance furnaces are either graphite or the cheaper Söderberg type (diameter of Söderberg electrode 0.5–2 m and current densities 2–3 A/cm²) type. The carbon paste for the Söderberg electrodes is filled into molds above the furnace. The electrodes are then baked by the heat produced by the current flow and the furnace, consequently they need not be pretreated in a separate furnace as is the case for graphite electrodes. Electrode consumption depends on the application, e.g., consumption of prebaked electrodes in steel production amounts to 5–15 kg per tonne steel, for ferrochromium (68% Cr) production 45–50 kg per tonne ferrochromium and for ferromolybdenum production 100–120 kg per tonne ferromolybdenum.

The electrodes can be arranged on the vertices of an equilateral triangle or in a row (three or six). The best arrangement for a particular application depends on parameters such as furnace efficiency, type of feed, and investment costs.

The type of *refractory* used in the walls and the roof of reduction furnaces depends on the

type of application and exposure it must withstand. They include magnesite, chrome magnesite, alumina, and graphite.

Figure 20 shows that the resistance heat is produced directly between the electrodes and the metal. The metal itself has a very low resistance and therefore produces very little heat. The resistivity of the slag, the slag depth, and the distance between the electrodes are the critical parameters controlling the amount of heat produced in the slag. The distance between the electrodes is chosen large enough to ensure that the current passes through the slag and metal and does not short-circuit between the electrodes (for six electrodes with diameter D the distance must be larger than $2.75D$; for three electrodes $\geq 2.6D$). Laboratory investigations have shown that pure resistance heating may be expected with electrode current densities up to 12 A/cm². Higher electrode current densities also show unstable arcing [103].

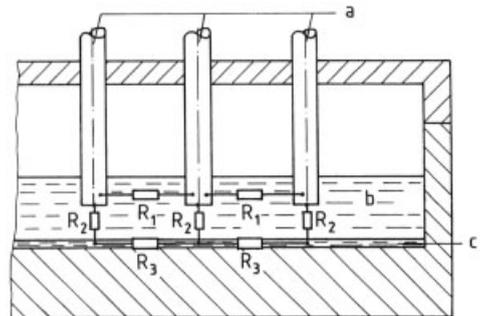


Figure 20. Flow of current through slag and metal in resistance furnaces, shown as a circuit containing resistances (R) [97]

a) Electrodes; b) Slag; c) Matte-metal

Figure 21 depicts the circulation of the slag, which can reach velocities between 20 and 30 cm/s close to the electrode, but < 1 cm/s in colder sections of the furnace. This circulation is created by:

- 1) Hot slag being replaced by colder slag from the surface due to density differences
- 2) Carbon monoxide bubbles at the electrode surface, which drag the slag upwards
- 3) Electromagnetic forces created by the current flowing between the electrodes (three-phase furnaces create a downward movement of the slag, whereas d.c. furnaces create an upward movement if the bottom electrode

is a cathode and an upward movement if the bottom electrode is an anode)

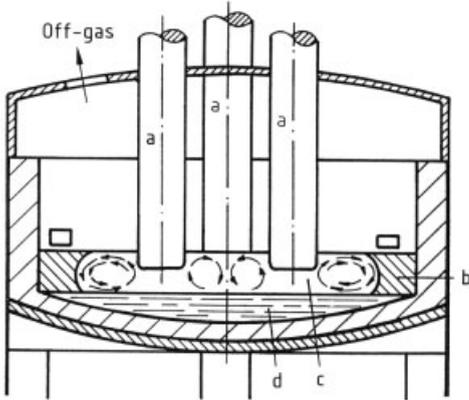


Figure 21. Flow distribution in resistance furnaces [82]
a) Electrodes; b) Dead volume; c) Slag; d) Matte – metal

In slag – matte furnaces the slag (40 – 150 cm deep) shows an upward circulation around the electrode. The movement is in the opposite direction in the matte (40 – 50 cm) due to electromagnetic forces (electrodynamics effects) and because the matte and slag flow in the same direction at the interface. In addition to the above-mentioned parameters affecting furnace operation, a number of operating parameters pertaining to the slag, can be modified to achieve optimal recovery of the valuable metals and compounds from the feed. These parameters are a function of the composition of the slag or material to be melted or smelted and temperature reached. They include:

- 1) Viscosity (Fig. 22), which affects the mixing and settling of the reduced and melted metal drops
- 2) Density differences between slag (iron slag: $\rho = 2.2 - 2.6 \text{ g/cm}^3$; copper slag: $\rho = 3 - 3.6 \text{ g/cm}^3$); matte ($\rho = 3.8 - 5.2 \text{ g/cm}^3$), speisses ($\rho = 7.2 - 7.5 \text{ g/cm}^3$) and metals effect the settling behavior of the phases or metals to be recovered
- 3) Resistivity, which has an effect on the amount of heat created and hence on the temperature via Joule's law
- 4) Oxygen permeability of the slag, a low oxygen permeability allows the required reducing conditions to be maintained within the metal – matte phase as well as in the slag

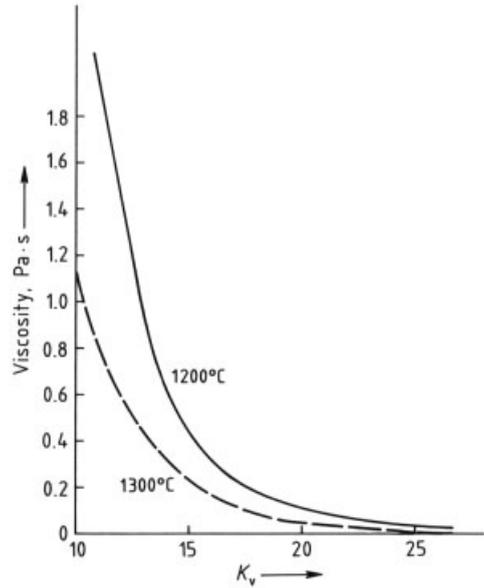


Figure 22. The viscosities of slags as a function of $K_V = (\% \text{FeO} + \% \text{Fe}_3\text{O}_4 + \% \text{CaO} + \% \text{MgO}) / (\% \text{SiO}_2 + \% \text{Al}_2\text{O}_3)$ and temperature [65], [102]

An additional factor which affects the performance of these furnaces is the residence time τ of the material to be treated in the reactor:

$$\tau = \frac{\text{active reactor volume}}{\text{volumetric flow of slag through the furnace}}$$

Tracer tests in a typical six-electrode resistance furnace for the production of Cu – Ni matte revealed that 65 % of the volume exhibits mixed flow characteristics, 1 % plug-flow characteristics, and 34 % is attributed to the dead volume [69, p. 274].

5.2.2.2. Metallurgical Significance

Reduction furnaces are used in many different processes for primary and secondary production:

- 1) Reduction of lead and zinc from oxidic materials (e.g., ores, roasted sulfidic ores, secondary oxidic materials)
- 2) Production of ferroalloys from oxidic ores (e.g., Ni, Cr, Mn, Si)
- 3) Ilmenite reduction to iron and a titanium slag
- 4) Iron and steel production from ores and pre-reduced pelletized iron ores

- 5) Matte production from sulfidic concentrates of copper and nickel
- 6) Production of calcium carbide and corundum
- 7) Cleaning of slag (i.e., recovery of valuable elements) produced by primary and secondary smelting operations (e.g., Pb, Cu)
- 8) Melting and cleaning of secondary metals (e.g., scrap)

Products include heavy metals and ferroalloys, mattes, special carbides, slags, and ceramics. The production of selected compounds will be treated in the following (→ Chromium and Chromium Compounds; → Manganese and Manganese Alloys; → Nickel; → Titanium, Titanium Alloys, and Titanium Compounds).

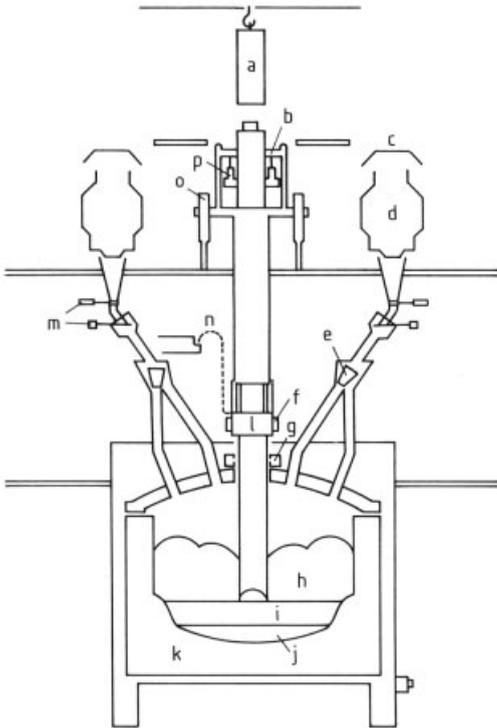


Figure 23. Schematic drawing of an electric FeNi reduction furnace [106]

a) Electrode addition; b) Holding ring; c) Ventilation hood; d) Calcine car; e) Charge diverter bucket; f) Pressure ring; g) Ventilation ring; h) Calcine; i) Slag; j) Metal; k) Refractory; l) Contact clamp; m) Change valves; n) Bus; o) Electrode hoist; p) Slipping ring

Production of Carbides. Calcium carbide furnaces (→ Calcium Carbide, Chap. 4.) belonged to the first reduction furnaces that were used on an industrial scale. The furnace feed

consists of calcined lime and coke that react to form calcium carbide and carbon monoxide when electric energy is transferred to the charge via electrodes. The original furnaces (ca. 1895) operated with direct current. One electrode was submerged in the feed, and the bottom of the furnace formed the other electrode. Alternating current replaced the direct current installations due to their low efficiency and the high investment costs for rectifiers. Presently the energy consumption of this process amounts to $3 \text{ MW} \cdot \text{h}$ per tonne calcium carbide.

Production of Ferroalloys. At several plants (Larymna in Greece, Cerro Matosa in Colombia, Doniambo in New Caledonia, Falconbridge in Dominicana, Inco in Guatemala) laterite ores are smelted to *ferronickel* in electric reduction furnaces (see Fig. 23). The ore is prereduced in rotary kilns at about $800\text{--}950^\circ\text{C}$ and continuously fed to the reduction furnaces opposite the slag tapping hole. Ferronickel is produced at $1500\text{--}1650^\circ\text{C}$ in the electric furnaces (three or six prebaked or Söderberg electrodes, diameter $1\text{--}1.3 \text{ m}$, electrode consumption several kilogram per tonne ferronickel) [70], [74], [75], [104–106] (→ Nickel, Chap. 8.2., → Nickel, Chap. 8.3.).

To produce *ferromanganese alloys*, manganese ores ($\geq 42\text{--}54 \text{ wt\% Mn}$) are mixed with flux (lime) and coke and either charged to a shaft furnace or an electric reduction furnace (→ Manganese and Manganese Alloys, Chap. 6.1.2.). For the production of low-carbon ferromanganese only the electric furnace is suitable. Energy consumption is $2100\text{--}8000 \text{ kW} \cdot \text{h/t}$ depending on the manganese, silicon, and carbon content (carburé, affiné, suraffiné) of the product [74], [75]. *Ferrochromium alloys* are produced in electric furnaces only. The Perrin process is applied for the production of low-carbon ferrochromium. Most of the high-carbon ferrochromium production is performed directly in electric furnaces. For the processing of chromite fines for high-carbon ferrochromium production, the route pelletizing, prereduction, and submerged arc furnace smelting may be followed [74], [75], [157] (→ Chromium and Chromium Alloys, Chap. 3.3.1., → Chromium and Chromium Alloys, Chap. 3.3.2., → Chromium and Chromium Alloys, Chap. 3.3.3.).

Ferromolybdenum (\rightarrow Molybdenum and Molybdenum Compounds, Chap. 6.3.), ferrotungsten (\rightarrow Tungsten and Tungsten Compounds), ferrovandium (\rightarrow Vanadium and Vanadium Compounds), ferrotitanium (Titanium and Titanium Alloys), phosphorus, (\rightarrow Phosphorus, Chap. 4.6.), ferrophosphorus (\rightarrow Phosphorus, Chap. 4.1., \rightarrow Phosphorus, Chap. 4.2.), and ferrosilicon (\rightarrow Silicon) are also products of submerged arc furnaces.

Production of Matte. The numerous examples of the production of Cu–Ni matte include (\rightarrow Nickel, Chap. 4.3.)

- 1) Inco at Thompson with two 30 MVA rectangular furnaces containing six Söderberg electrodes (diameter 2 m) to produce a Cu–Ni matte with 26 % Cu + Ni at 400 kW · h per tonne charge [105]
- 2) Falconbridge with two 33 MVA rectangular furnace each having six electrodes producing Cu–Ni matte with 24 % Cu + Ni [104]
- 3) Rustenburg with a 19.5 MVA rectangular furnace with six electrodes (diameter 1.24 m) producing a matte with 24 % Cu + Ni [69]
- 4) Mufulira with a 36 MVA rectangular furnace with six electrodes (diameter 1.6 m) to produce a Cu matte using less than 400 kW · h per tonne [69].

Production of Ti Slags. Some large plants treat ilmenite for the production of a slag containing 75–85 % TiO_2 and iron (\rightarrow Pigments, Inorganic, Chap. 2.1.2.2.).

Among them are the plants of Quebec Iron and Titanium Corporation in Canada, Richard's Bay Iron and Titanium in South Africa, and Tinfos Titan & Iron in Norway.

Slag Cleaning [84], [108], [157]. In order to produce an environmentally clean slag and optimize recovery, slag cleaning operations often follow the primary and secondary production of metals such as lead and copper. This implies that heavy metal, matte, and oxide are recovered as far as possible.

Slag cleaning is mostly carried out in separate resistance furnaces, for example at several *copper smelters* employing the Outokumpu process (e.g., Onsan, KGHM-Głogów, Hidalgo, Hindus-

tan, Norddeutsche Affinerie, Botswana Concession Limited, Rio Tinto) [84]; at Kamioka [99] where lead and zinc are recovered from slags; and in the Mitsubishi process for the production of copper at Naoshima and Timmins [84].

A slag-cleaning or reduction furnace is, however, sometimes directly integrated in the primary smelter, as for example in three Outokumpu furnaces and the Kivcet furnaces (Fig. 24). The Kivcet furnace is used for the *production of lead from sulfide ores* (\rightarrow Lead, Chap. 4.4.2.1.). In this operation the dry feed is oxidized and smelted in suspension in the reaction shaft (c) of the furnace during which most of the lead enters the slag phase as lead oxide. Most of this slag is reduced in the lower part of the reaction shaft by coke breeze floating on top of the liquid phases (metal and slag). Metal and slag continuously underflow a barrier to the slag-cleaning or reduction section of the furnace, in which three electrodes (a), placed in a row, transfer electric power to the melt. Additional coke is added to produce an atmosphere that reduces the remaining lead oxide to lead, which then collects at the bottom of the furnace. Some zinc oxide is also reduced to zinc, which evaporates and reoxidizes in the gas phase and is recovered from the filters in the off-gas cleaning units. Lead leaves the furnace by a syphon [101], [107].

Other slag-cleaning furnaces have been positioned downstream of copper or lead secondary smelting furnaces, and converters (e.g., at Metallurgie Hoboken, Belgium and USMR smelter of AMAX, New Jersey). Typical process data for slag reduction and slag cleaning processes are given in Table 10.

5.2.3. Refining Resistance Furnaces [57], [129], [130], [154]

The *electroslag refining process* (ESR) is the classical example for refining operations in a resistance furnace. The high resistance of the slags (CaF_2 – CaO – Al_2O_3) is used to produce enough heat to melt and refine high-grade steels (\rightarrow Steel) and titanium (\rightarrow Titanium, Titanium Alloys, and Titanium Compounds). The main components of the furnace are its consumable electrode (raw material), a water-cooled mold, and a bottom plate, which are connected to an alternating current source (Fig. 25). Initially the

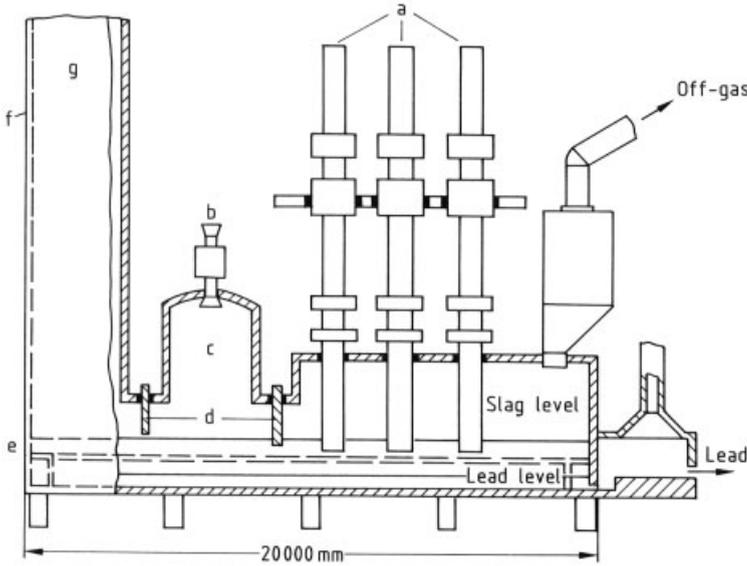


Figure 24. The Kivcet reactor for the production of lead [101], [107]

a) Electrodes; b) Concentrate burner; c) Smelting shaft; d) Partition walls; e) Belt of water-cooled elements; f) Water-cooled refractory lining; g) Gas removal shaft

Table 10. Production data for electrothermal slag reduction in various processes

Application	Estimated number of plants	Production capacity, 10^3 t/a	Furnace size, MVA	Energy consumption, kW · h/t
Cu flash smelting	30–35	10 000	6–10	50–100
Pb flash smelting	2			
Conventional Pb reduction	5	500	3–6	150–700
Secondary Cu smelting	2	200	6	150–200

electrode (a) is submerged in a high-melting liquid slag (b), the mold (e) and bottom plate (f) contain the slag. At sufficiently high voltages the liquid slag starts to melt the consumable electrode at its surface. The molten metal collects at the tip of the electrode and drops through the slag. During this process it is refined due to its interaction with the slag. The molten metal collects in the mold, and the bottom plate moves downwards at the same rate as that of metal production. The refined metal is cooled by the water-cooled mold and solidifies. The mold and bottom plate are made of copper and water cooled to prevent reactions and to ensure high heat transfer (Fig. 26). This cooling system is responsible for high energy losses (see Tables 3 and 7).

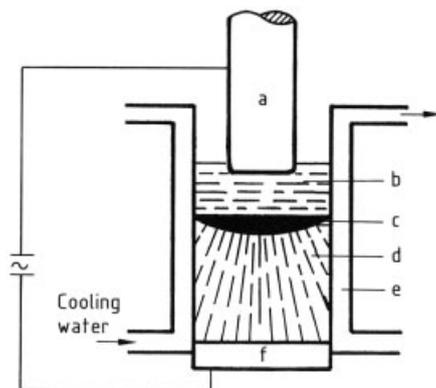


Figure 25. Sketch of an electroslag refining furnace [73]
a) Consumable electrode; b) Slag; c) Molten metal; d) Solid metal; e) Water-cooled mold; f) Movable cooled copper plate

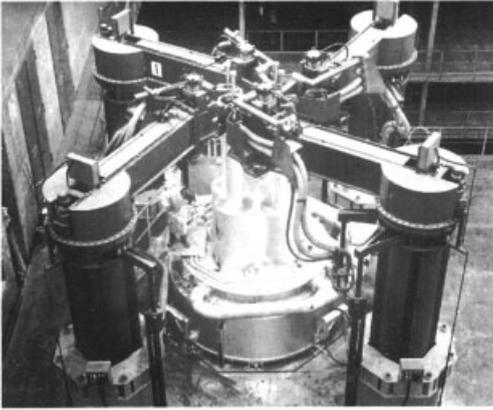


Figure 26. An industrial ESR plant at Saarstahl GmbH [65], [130]
Maximum block diameter 2.3 m, maximum block mass 160 t, with a remelting rate of 2.3 t/h

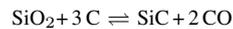
ESR processes can also be used to *remelt and refine secondary materials* in a single step. Reactor construction is similar to that described above for the standard ESR, the only difference being that a nonconsumable electrode is used and material is fed in particulate form.

5.2.4. Solid-State Resistance Furnaces [63], [71]

The feed material for this type of furnace has a high electric resistance. A current is applied to the feed via two electrodes and the heat generated permits the desired reactions to take place in the solid state. Two typical applications are the graphite furnace and the silicon carbide furnace (see below).

Graphite Furnace (\rightarrow Carbon). In this furnace petroleum coke is converted into graphite which is used for electrodes in other electrothermal furnaces. The feed (petroleum coke with tar as a binder) is mixed and usually extruded into the desired shape of the electrodes. The electrodes are heated up to 800–1300 °C in fuel-heated furnaces to carbonize the binder. Subsequently the electrodes are charged to a resistance furnace (20 m \times 4 m \times 4 m), where they are stacked parallel to the face sides (Fig. 27). The void areas are filled with crushed graphite to ensure that the electrodes are in good electric contact with one another. An electric current flows through the furnace and produces the operating temperatures (2400–2800 °C). The amorphous coke is transformed to graphite (hexagonal lattice) within several days. Since the conductivity of the amorphous coke is much lower than that of graphite, the furnace voltage is changed in order to maintain the required temperature. The energy consumption for this process is 4–6 MW · h per tonne graphite for a connecting power of 5–16 MW. Such a graphite furnace produces ca. 50 t graphite per batch.

Silicon Carbide Furnace. (See also \rightarrow Silicon Carbide). In this case two solid materials (sand and coke) are mixed and filled into a furnace which is similar to that used for graphite production. The reaction



takes place in the solid state. The sand–coke mixture (with additions of sawdust and sodium chloride) is charged into the furnace around a central core of graphitized coke (Fig. 28). This

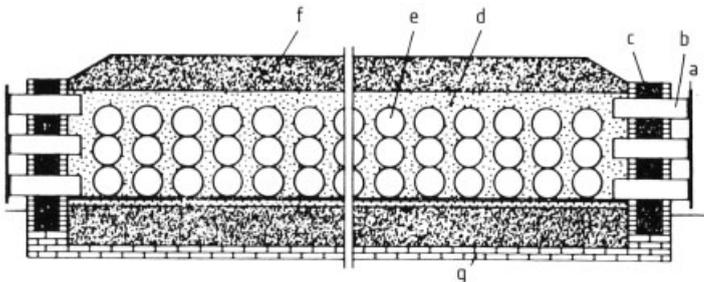


Figure 27. Sketch of a graphitizing furnace [63]

a) Current supply; b) Electrodes; c) Furnace head; d) Resistance body; e) Electrodes to be graphitized; f) Carborundum layer; g) Furnace bed

central core is connected to electric power and the coke is used as a conductor, which reacts in a similar way as described in the graphitization furnace above. Silicon carbide formation starts at 1700 °C, at 2400–2500 °C a coarse crystalline product is formed. Sodium chloride is added to evaporate undesired elements such as aluminum, iron, and titanium as chlorides. Only ca. 20–30 % of the reaction product is high-grade material. Energy consumption is between 8.5 and 12.5 MW · h per tonne silicon carbide.

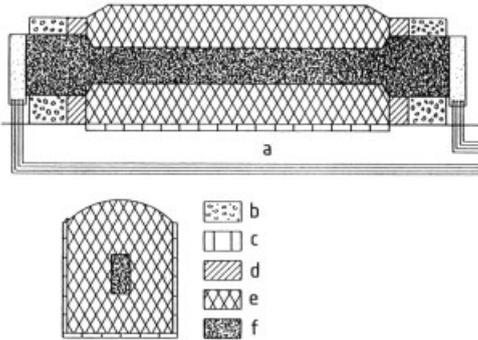


Figure 28. Sketch of a silicon carbide furnace without degassing from the furnace bottom [63]
a) Current supply; b) Fire clay concrete; c) Fire clay bricks; d) SiC-protection layer; e) Reaction mixture; f) Electrode and resistance core

5.3. Arc Furnaces

5.3.1. Basic Principles [55], [56], [67]

An electric arc can be produced and sustained between two electrodes or an electrode and a liquid melt if the voltage is high enough. The transformation of electric energy to heat takes place through the current in the ionized plasma of the arc, in which the temperatures may reach 6000 °C.

Electric arc furnaces may be classified according to whether transfer of heat from the arc to the furnace feed is indirect or direct. In indirectly heated furnaces (Fig. 29 A), the arc burns between two electrodes without contact with the feed; heat is transferred solely by radiation and convection. This technique was employed in single-phase rotary furnaces, which are, however, no longer in use because they are not economical. In directly heated furnaces (Fig. 29 B) an arc burns between the electrode and the melt.

Heat is transferred via the fire point produced by the arc by conduction, radiation, and convection to the melt. Directly heated arc furnaces can be used for melting and refining.

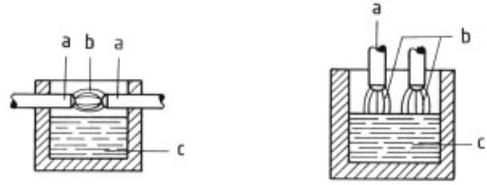


Figure 29. Indirectly (A) and directly (B) heated arc furnaces [67]

a) Electrodes; b) Arc; c) Liquid melt

The arc-resistance and submerged-arc furnaces mentioned in Section 5.2 are mainly used for reduction. Since their construction is similar to that of resistance furnaces the discussion is not repeated here.

5.3.2. Electric Arc Furnaces [109–112], [154]

Today, 32 % (240×10^6 t/a) of the total world steel is produced in electric arc furnaces, this is their principal application (→ Steel).

Furnace Construction. One-electrode furnaces usually operate in the d.c. mode with the electrode forming the cathode and the bottom of the furnace forming the anode (e.g., 11 MW furnace at Florida Steel Corporation for melting scrap, electrode diameter 0.45 m, electrode consumption 2 kg per tonne steel). This kind of furnace may, however, also be operated in an a.c. mode [111].

Three-electrode furnaces (Fig. 30) are mostly a.c. furnaces. The electrodes (a) are switched into a three-phase circuit and are usually placed on the vertices of an equilateral triangle in a round furnace.

Most furnaces are equipped with removable roofs in order to charge via baskets from the top. The charging of sponge iron, for example, takes place batchwise in baskets or continuously through tube feeding systems. The required atmosphere can be provided inside the furnace which can be tilted during tapping.

Dolomite and magnesite are the refractories mostly used for lining the lower walls and the bottom of the steel shell of the arc furnaces.

The upper walls and the roof of the furnaces are water-cooled to provide good resistance against high temperature and temperature changes. The high temperature obtained in arc furnaces allows high production capacities. When scrap is melted down, crater-type holes are burnt into the scrap which protect the furnace roof and walls from overheating.

Modern furnaces may be tilted only 12° during slagging off operations, steel tapping (Fig. 30) is done by eccentric bottom tapping. Sometimes the mixing in the furnace is improved by an induction stirring coil underneath the furnace or by bubbling gas through a porous plug.

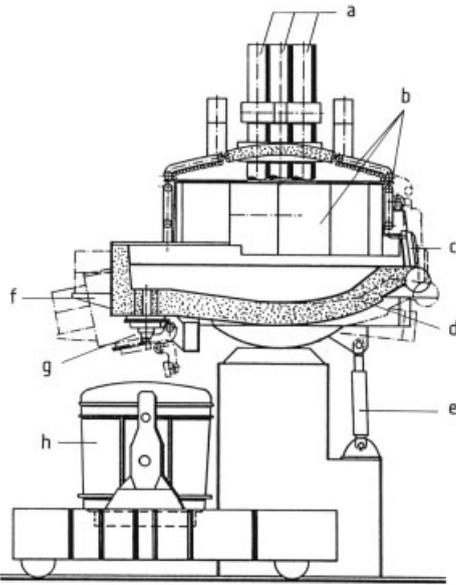


Figure 30. Typical three-electrode arc furnace with water-cooled walls and roof, and eccentric bottom tapping for steel production [65], [78]

a) Electrodes; b) Water-cooled walls and roof; c) Tiltable furnace; d) Refractory lining; e) Tilting mechanism; f) Spout; g) Eccentric tapping; h) Ladle

Metallurgical Significance. The advantages of electric arc furnaces are listed below:

- 1) High temperatures can be reached within a short time
- 2) Continuous temperature adjustment is possible via computer control systems which control the level of the arc
- 3) The atmosphere in the furnace can be tightly controlled

- 4) In contrast to conventionally heated furnaces, impurities are not brought into the steel by the energy input (e.g., sulfur by coke)
- 5) The furnace can easily be brought on- or off-line with relatively little energy and time, furnace operation may be controlled to meet the production requirements of the cast shops and mills.
- 6) Oxidation, reduction, and alloying can be carried out in one charge with little loss
- 7) Desulfurization is possible

Development of arc furnace technology has led to the construction of ultrahigh power (UHP) furnaces [63], [109] with a connected power (MVA) to feed (tonnes) ratio $\leq 1 : 2$. Examples of UHP furnaces are given in Table 11. The excellent electrical efficiency of these furnaces can be attributed to low Joule-effect losses and conductors with small cross sectional areas. The short, high-current arcs improve heat transfer. These furnaces are computer controlled (energy input, phase balancing, and regulation of cooling water flow rates in the electrodes, walls, and roof). For a 24 MVA furnace (diameter 4.6 m, weight 40 t, electrode diameter 0.45 m) power consumption amounts to $560 \text{ kW} \cdot \text{h/t}$, which decreases to $< 500 \text{ kW} \cdot \text{h/t}$ for a 90 MVA furnace (diameter 7 m, weight 150 t, electrode diameter 0.6 m).

5.3.3. Vacuum Arc Refining (VAR) Furnaces [129], [130], [154]

Furnace Construction. Vacuum arc furnaces are normally used for consolidation and refining reactions. The raw material (sponge or scrap) is pressed into an electrode shape, which is used as a consumable electrode in the arc furnace. Normally d.c. current is used to provide a stable arc between the consumable electrode and the counter electrode at the bottom of the furnace (Fig. 31). After the arc is ignited the electrode starts to melt, volatile elements and entrapped gases are removed through the high temperature and the vacuum conditions. The refined metal drops to the water or liquid Na/K-cooled copper bottom where it solidifies. Copper is used as the mold material to prevent reactions with refractories.

Table 11. Process data for examples of arc furnaces (> 100 t) [112]

Company, location	Furnace capacity, t	Capacity, 10 ³ t/a	Power, MVA *	Specific power, kVA/t	Electrode diameter, mm	Furnace diameter, mm
Thyssen, Oberhausen, Germany	130	600	96 AC	740	610	7050
Krupp, Bochum, Germany	140	550	85 AC	710	610	7000
Toshin – Azuma Steel, Himeji, Japan	150	600	66 AC	440	610	7000
Chaparral Steel, Midlothian, United States	150	800	138 AC	920	610	6710
Lukens Steel, Cloatesville, United States	160	800	67 AC	420	610	6710
Terni, Italy	180	500	110 AC	611	600	7300
Nakorntai strip, Chonburi, Siam	180	1500	130 AC	722		8700
North Star, Delta, USA	163	1360	140 AC	848	600	7300
Nucor Steel, Nicoman USA	155	1000	164 DC		711	7315
Nylsa, Monterrey, Mexico	135	900	120 DC		711	7315
Megasteel, Klang, Malaysia	160	1200	160 DC		800	7100

* Power for transformer

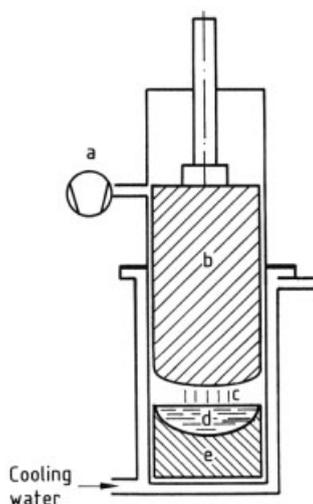


Figure 31. Typical vacuum arc refining furnace with consumable electrode [110]

a) Vacuum pump; b) Consumable electrode; c) Arc; d) Molten metal; e) Solid metal

VAR furnaces may also be used with a permanent electrode if the material is fine scrap [110]. This is fed in separately. These furnaces are also used for alloying high-melting metals such as niobium, tantalum, or titanium.

Metallurgical Significance. Molten titanium is very reactive, as are molybdenum and zirconium. These metals must therefore be melted in a controlled atmosphere or a vacuum. Vacuum arc refining furnaces are thus suitable for melting and/or recycling these highly reactive metals (also possible in electron-beam

furnaces). As with ESR furnaces, metal sponge and scrap may be mixed and pressed into consumable electrodes and used as such in the VAR furnace. Often refining involves several steps to achieve a pure product, this explains the relatively high energy consumption for titanium (3.8 MW · h per tonne titanium produced).

Vacuum arc furnaces are also used to degas certain steel grades during remelting, energy consumption is ca. 1.0 MW · h per tonne produced metal.

5.4. Induction Furnaces [80], [89], [113–118], [129], [130], [154]

The increasing demand for high-quality metals and alloys under ecologically clean conditions has increased the application of induction furnaces in foundries for cast iron, steel, and non-ferrous metals (mainly Al, Cu, Mg, Ni, precious metals and their alloys). At least 20 % of metals produced by electrothermal reactors are melted in induction furnaces.

There are two basic types of induction furnace construction: the crucible induction furnace and the channel induction furnace (Figs. 32 and 33). In this chapter discussion of the application of induction furnaces is mainly limited to melting and refining of metals and alloys [56], [65], [81], [94], [95], [119]. Special applications are zone refining and levitation melting [58], [81]. Inductive heating is also used for brazing and welding, different types of heat treatment

(e.g., surface treatment, heating and annealing), metal transport and dosing, and electromagnetic casting (EMC) [56], [65], [81], [94], [95], [119]. Since these processes do not occur within reactor vessels, they will not be discussed here.

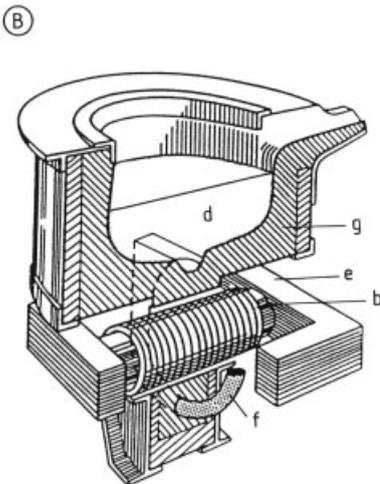
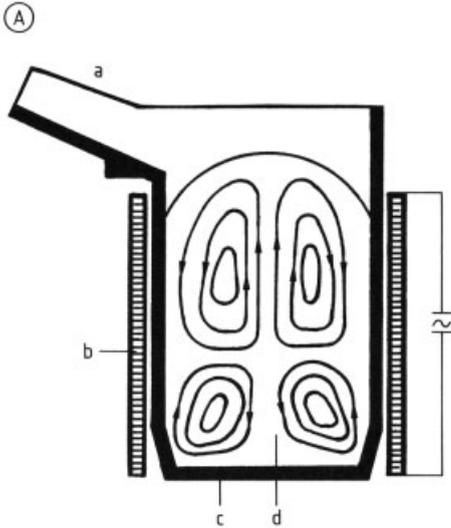


Figure 32. Crucible induction (A) and channel induction (B) furnaces [65]

a) Spout; b) Induction coil; c) Crucible; d) Molten metal; e) Iron core; f) Channel; g) Rammed lining

5.4.1. Basic Principles [55], [56], [67], [78], [81], [154]

Electromagnetic induction heating is a direct method for contactless heating with a high power density which implies that the material to be heated (melted) is not contaminated by heating gases or electrode materials. However, contact and reactions with the crucible (graphite or refractories) may take place. Advantages of these types of furnaces are excellent alloying and mixing conditions, good temperature control of the melt, a low dross formation, and low off-gas volume.

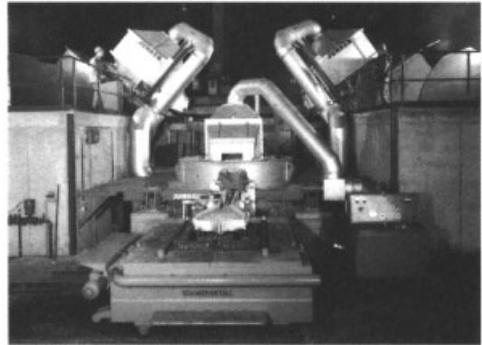


Figure 33. A 30-t channel induction furnace between two 24-t crucible induction furnaces [65]

The heating principle is as follows: an a.c. coil induces a potential in an electrical conductor (in induction furnaces solids and/or melts) situated inside the coil due to the changing magnetic field, which creates eddy currents (Lenz's law). The eddy currents or induced current produce heat according to Joule's law (see Section 5.2.1)

$$U_{\text{ind}} = -\frac{w d\Phi}{dt} \quad (\text{Lenz's law})$$

where U_{ind} is the induced potential (V), Φ the magnetic field strength (Tesla), and w the number of coil windings.

The resistivity and relative magnetic permeability of the material to be heated and the frequency of the primary current circuit are the most important parameters of induction heating. The induced current within the conductor is not evenly distributed, but mostly located near the surface (skin effect, Fig. 34).

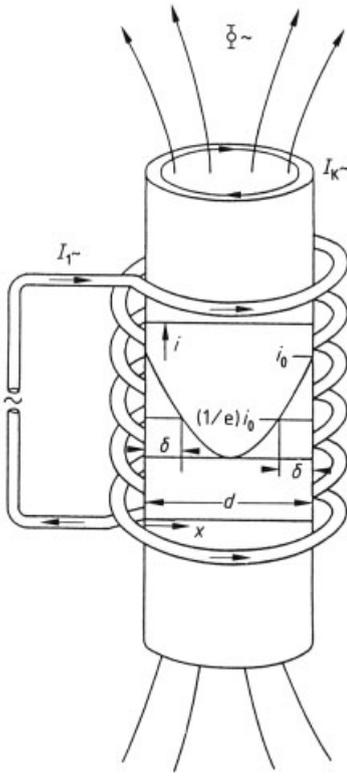


Figure 34. Inductive heating of a metal cylinder [81]
 δ = current penetration depth = $(1/e) i_0$; d = diameter;
 I_1 = inducing current; I_K = induced current; i_0 = surface
 current

5.4.2. Furnace Construction [55], [56], [67], [78], [81], [154]

5.4.2.1. Crucible Induction Furnace

Crucible induction furnaces have a cylindrical induction coil consisting of water-cooled copper tubes. The crucible is located inside the coil and usually consists of rammed or brick refractories, graphite, or clay-graphite. In rare cases a more expensive prefabricated ceramic or steel crucible may be used (Fig. 32 A and 33). An interesting development is the inert cold-wall induction crucible.

The crucible can and should be covered to reduce heat losses. For special applications (metal distillation, refining, melting of reactive or high-quality metals and alloys, etc.) the furnace is operated as a vacuum or controlled atmosphere induction furnace [58], [93].

There are two basic types of vacuum induction furnace, the compact vacuum crucible induction furnace and the vacuum chamber induction furnace (Figs. 35 and 36). The *compact vacuum crucible induction furnace* (Fig. 35 A) is operated at a low vacuum (ca. 10^{-3} bar). It has a simple design and lower investment costs than the vacuum chamber induction furnace, but the load capacities can be higher. The coil, vacuum chamber, and crucible form an integrated unit. In contrast, the crucible and induction coil of a *vacuum chamber induction furnace* (Fig. 35 B and 36) are located within a sealed, water-cooled chamber. It allows a vacuum of up to 10^{-9} bar and permits the metal to be poured under vacuum within the sealed chamber [56], [94], [95], [154].

Industrial induction crucible furnaces have different sizes (up to 60 t) and are operated at different frequencies (typically up to 500 Hz), under air or vacuum. Laboratory scale furnaces have capacities down to a few grams and frequencies reaching up to MHz range. Electrical efficiency is $> 60\%$.

One of the biggest advantages of a crucible induction furnace is the excellent bath mixing behavior. Interaction of the magnetic field and electrical currents create electromagnetic forces, which leads to the elevation of molten metal in the center of the bath and mixing (Fig. 32 A).

As a result of stirring, crucible induction furnaces can melt loads of small pieces of material (e.g., swarfs, chips), which are rapidly drawn into the bath. This facilitates operations such as alloying and refining, and ensures a uniform bath composition. The scale of mixing is inversely proportional to the applied frequency.

The diameter of the charged material d has to be at least 3.5 times larger than the penetration depth δ of the induced current to ensure maximum transference of power (Fig. 37). The minimum charge to start melting should be 20% of the crucible capacity. In most cases the starting amount is two-thirds of the crucible capacity.

Metallurgical Significance. Crucible induction furnaces are used for melting and refining numerous metals and alloys. They are usually applied in cast iron, steel, and nonferrous metal foundries (aluminum, magnesium, copper, brass, bronze, zinc, nickel, precious metals,

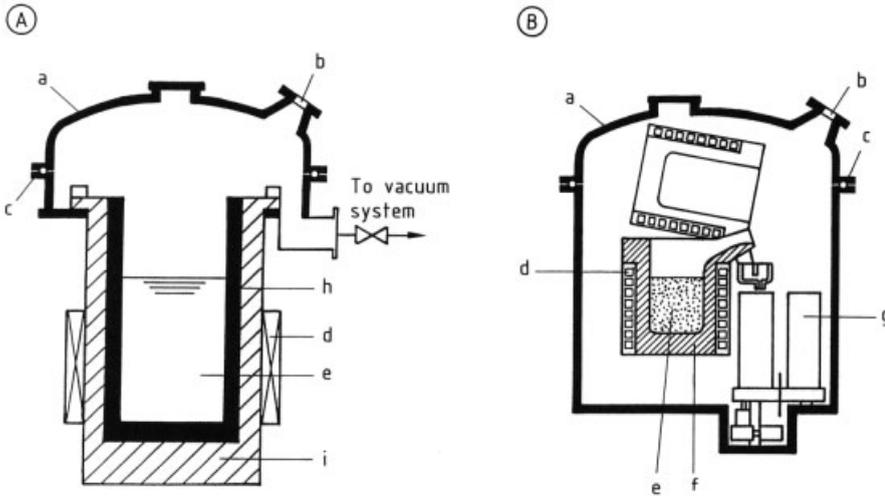


Figure 35. Compact vacuum crucible and (A) and vacuum chamber (B) induction furnace [56], [65]
 a) Water-cooled vacuum hood; b) Viewing glass; c) Vacuum seal; d) Induction coil; e) Molten metal; f) Tilttable crucible; g) Centrifugal casting setup; h) Crucible; i) Rammed lining

superalloys). They are unsuitable for slag metallurgical operations since only the metal is heated by induction and not the slag. In addition the advantages of numerous crucible designs (e.g., rammed or brick lining; ceramic, graphite, steel, or copper crucible) render them very attractive. They also permit various operations, such as alternative or continuous melting, continuous melting and pouring, quick alloy changes, and application of vacuum or controlled atmosphere. They are sometimes used as buffer furnaces or grading furnaces.

Line-frequency crucible induction furnaces (Table 12) are mainly employed in cast iron, heavy metal, and aluminum foundries. They are sometimes used in (high-grade) steel foundries. High furnace capacities are possible.

Medium-frequency crucible induction furnaces (Table 13) are mainly used in operations that require frequent alloy changes for melting high-grade steel, alloyed cast iron, copper, aluminum, and precious metals in medium-size furnaces. The low power input required for holding furnaces means that short induction coil furnaces can be used for these applications.

If possible, the crucibles have a rammed lining (acidic monolithic linings) due to their lower costs, which produces significant savings in larger furnaces. They are widely used in cast iron, steel, and nonferrous metal foundries, es-

pecially in furnaces with high capacities and little or no metal and alloy changes. The linings are partially infiltrated by the metals/alloys and hence cause contamination during an alloy change. Nonferrous metal foundries, which frequently change alloys often employ more expensive prefabricated crucibles. Precious metal foundries need prefabricated crucibles to minimize metal losses in the linings. Magnesium and its alloys are melted solely in steel crucibles due to their chemical behavior. Alloys that attack acidic linings require basic linings (Al_2O_3 , MgO) or graphite crucibles. Nonconducting materials (e.g., quartz and glass) are melted in graphite crucibles which heat the charge at low temperature.

5.4.2.2. Channel Induction Furnace

In the channel induction furnace the induction coil is located under or beside the crucible and has an iron core. The coil is enclosed in a channel (Fig. 32 B). This construction acts as a transformer with a short-circuit secondary coil producing the best power transfer efficiency (0.95 to 0.98; furnace efficiency amounts to 0.9). The metal in the channel is heated and pumped back to the metal reservoir in the crucible by the repulsive force of the coil and the induced currents.

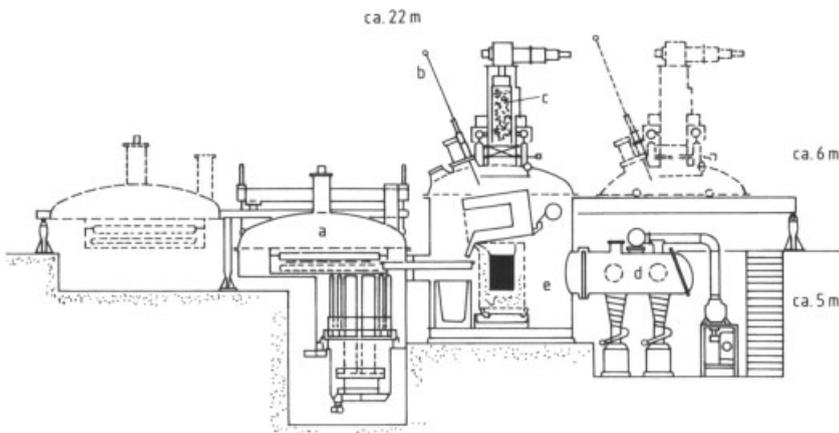


Figure 36. Multichamber vacuum induction furnace [65]

a) Mold chamber; b) Bridge breaker; c) Charging chamber; d) Vacuum pumping system; e) Melt chamber

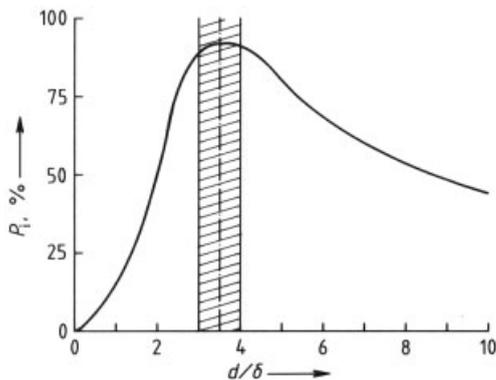
Table 12. Process data for examples of line-frequency crucible induction furnaces [133]

Product	Pouring temperature, °C	Range of			Energy consumption, kW · h/t
		Capacity, t	Power, MW	Melting rate, t/h	
Cast iron	1500	0.75	0.3	0.47	610
		60.0	17.0	32.5	545
Steel	1650	0.75	0.25	0.32	740
		60.0	17.0	29.5	570
Copper	1200	0.6	0.15	0.32	465
		36.4	7.0	20.0	385
Brass	1000	0.6	0.15	0.51	320
		35.0	7.0	26.0	270
Aluminum	700	0.8	0.24	0.42	570
		12.0	3.8	7.3	530

Table 13. Examples of medium-frequency crucible induction furnaces [133]

Product	Pouring temperature, °C	Range of			Energy consumption, kW · h/t
		Capacity, t	Power, MW	Melting rate, t/h	
Cast iron	1500	0.08	0.16	0.23	600
		17.0	8.0	16.0	520
Steel	1650	0.08	0.16	0.21	650
		17.0	8.0	14.5	545
Copper	1200	0.15	0.16	0.32	500
		19.5	4.0	10.0	390
Brass	1000	0.15	0.16	0.41	350
		18.6	4.0	14.0	265
Aluminum	700	0.25	0.25	0.45	580
		6.2	3.0	5.7	530

This means that the furnace must always be charged with a certain amount of molten metal.

**Figure 37.** Power absorption P_i as a function of the standardized particle diameter d/δ

Various designs of channel induction furnaces exist: inclined and vertical channel furnaces, horizontal channel furnaces, and open channel furnaces. They are normally used as holding or casting furnaces and less frequently

as melting furnaces. Due to large flow rates in the channel they are more susceptible to erosion of the refractory within the channel, however, they permit high capacities and power efficiency is greater than 80% which is larger than that for crucible induction furnaces. Large holding furnaces may have more than one channel. The quantity of refractory materials used for channel furnaces is high. Careful maintenance of the channel is also necessary.

Metallurgical Significance. Due to the relatively low specific power requirements, channel induction furnaces are mainly used for holding and superheating cast iron and nonferrous metals, but less often for steel. Channel induction furnaces may have high capacities (up to ca. 250 t), especially in the iron industry (holding and superheating iron from blast furnaces prior to refining in the oxygen converter: up to 1500 t, 15 MW [56]). They are often used in combination with other furnaces and act as buffer furnaces. They are sometimes used as melting or

casting furnaces, these include automatic air-pressure pouring systems (Fig. 38).

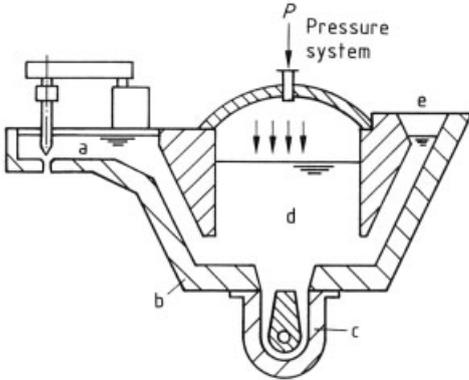


Figure 38. Automatic air-pressure pouring system [56]
a) Casting system; b) Rammed lining; c) Inductor; d) Molten metal; e) Charge system

Channel induction furnaces are not as widely applied as crucible induction furnaces in non-ferrous industries. Clogging of the channel is a handicap, especially in the melting of aluminum. However, the different designs of channel inductors permit various applications, such as coating pots (zinc) or pouring furnaces.

Various data for channel induction furnaces are given in Tables 14 and 15.

5.4.2.3. Special Induction Furnaces

Reactions with the crucible or refractory material are undesirable for special high-grade metals and alloys. Use of special induction coil design and suitable frequencies and induction currents, allow metals or alloys to be melted and centered inside the coil by levitation melting. This melting method is only used on a laboratory scale for small amounts of pure metals and alloys.

Induction zone melting is used to refine very pure metals or alloys, especially for the production of semiconductors (\rightarrow Crystal Growth, Chap. 6.4.). Germanium and silicon mono crystals are produced by this technique.

5.5. Plasma Furnaces

A plasma is a partially ionized (up to 50%) gas that contains electrons, ions, energized molecules, dissociated molecules, neutral

molecules, and atoms (\rightarrow Plasma Reactions). The plasma operates at atmospheric pressure and is sufficiently conducting to permit stable transfer of electric power between two or more electrodes. The plasma attains temperatures > 2000 K (e.g., 10 000–20 000 K for an argon plasma operated at an arc voltage of 25 V and current of 1.5 kA).

Basic Principles and Construction [56], [61], [62]. The principal difference between plasma furnaces and arc furnaces is the use of a plasma torch instead of electrodes.

In a plasma torch thermionic electrons are emitted from a cathode and accelerated towards the anode. They collide with gas molecules and ionize them. The positively charged gas ions are accelerated in the opposite direction towards the cathode with which they collide, releasing their energy and hence sustaining the thermionic emission. Depending on the type of torch and its construction materials, water cooling may be applied. Various a.c. or d.c. torches are available; they include transferred arc (Fig. 39 A), non-transferred arc (Fig. 39 B), and superimposed arc.

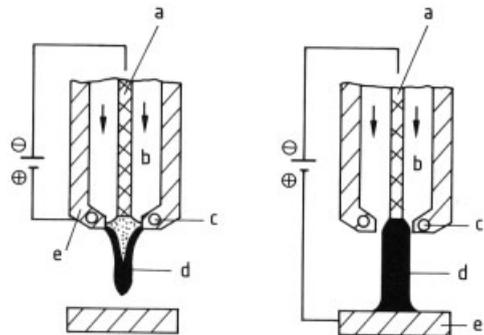


Figure 39. Transferred (A) and nontransferred (B) arc torches [83]

a) Cathode; b) Plasma gas; c) Cooling water; d) Plasma jet; e) Anode

Furnace construction is similar to that of arc resistance and arc furnaces. Refractories and other components are selected to suite the specific application.

Metallurgical Significance [62], [120], [130], [155]. Plasma furnaces have only recently been introduced into primary and secondary metallurgy. Examples include:

Table 14. Examples of channel induction furnaces for melting [133]

Product	Pouring temperature, °C	Range of			Energy consumption, kW · h/t
		Capacity, t	Power, MW	Melting rate, t/h	
Copper	1200	1.0	0.2	0.60	270
		26.0	3.3	11.2	280
Brass	1000	1.0	0.2	0.93	200
		26.0	3.3	18.5	175

Table 15. Examples of channel induction furnaces for holding and pouring cast iron (pouring temperature 1500 °C) [65].

Capacity, t	Power, MW	Throughput, t/h	Holding power, kW
10.0	0.3	7.2	145
10.0	0.5	12.0	145
115.0	1.2	27.0	390
115.0	3.0	87.0	390

- 1) Remelting of steel scrap (e.g., former VEB Edelstahlwerke, Freital, Germany: 35-t furnace with three plasma torches, total power input 19.8 MW, melting capacity of 20 t/h [121]; Voest-Alpine AG, Linz, Austria: 45 t-furnace (Fig. 40) with four plasma torches, total power input 24 MW, melting capacity ≤ 25 t/h [122])
- 2) Production of ferrochromium from chromite fines and the refining the high-carbon ferrochromium (e.g., 40 MVA d.c. one electrode furnace, diameter 9 m, height 3.8 m, Middelburg Steel and Alloys, South Africa) [62], [64], [123])
- 3) Recovery of aluminum from aluminum dross (e.g., ALCAN, Canada using one 1.5-MW torch for each of two 9-t rotating furnaces) [124])
- 4) Recovery of FeNiCr alloy, slag, and lead and zinc from flue dusts in the stainless steel industry (e.g., three \times 6-MW torches, SCANDUST in Landskrona, Sweden producing 70 kt/a) [62], [125])
- 5) Plasma cold hearth melting is used for melting Ti alloys. Furnaces up to 3.5 MW are in operation [155])
- 6) Several units use plasma torches in research furnaces (e.g., SKF, Tetronics, Krupp) [62])

5.6. Electron-Beam Furnaces

Basic Principles [56], [58], [59], [156]. In electron-beam furnaces the kinetic energy of highly accelerated electrons in a vacuum is transferred to the surface of a material on impact. This leads to local temperature increases and melting of the material.

Furnace Construction [56]. The principle component of an electron-beam furnace is the electron gun which may be work-accelerated or self-accelerated. The self-accelerating gun is most commonly used. Here the voltage is applied between the cathode and an auxiliary hollow anode situated just below the cathode. In work-accelerated guns the anode is the material to be melted, this techniques is used to good advantage in zone melting.

The self-accelerating electron gun (Fig. 41) consists of an electron emitting cathode (a), an accelerating hollow anode (c), and electromagnetic focusing and deflection coils (d). In addition to the gun the furnace comprises of a work chamber in which melting and refining is performed in water-cooled crucibles, vacuum equipment for the electron gun and work chamber, and a computerized control system which controls and monitors the operating parameters.

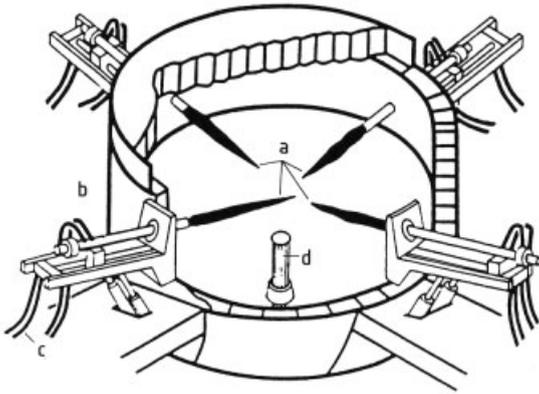


Figure 40. Schematic drawing of the Voest – Alpine furnace for remelting steel scrap [62]
a) Plasma zones; b) Plasma torch; c) Cathode; d) Anode

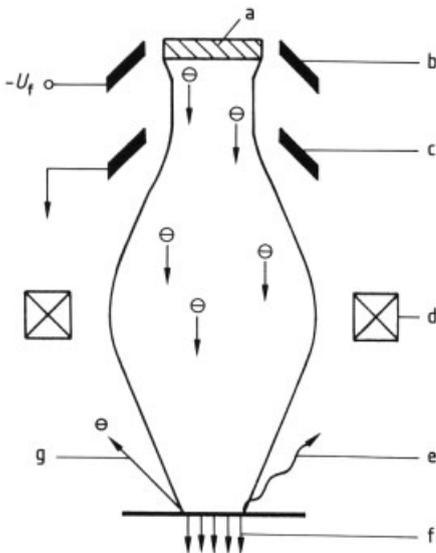


Figure 41. Self-accelerating electron gun [56]
a) Cathode; b) Control electrode; c) Anode; d) Electromagnetic lens; e) Secondary electromagnetic radiation; f) Electron beam penetration; g) Reflected and secondary electrons

Various types of self-accelerating guns and gun configurations have been developed; they include annular, axial (or Pierce), axial differential pumped, transverse and radial multifilament gun arrangements.

Feeding of material to the furnace is facilitated by drip melting of vertically or horizontally fed consumable electrodes, or bath melting of granulated material and scrap. The melted product may be continuously cast into bars or molds.

Metallurgical Significance [58], [59], [155]. Although electron-beam melting has higher investment costs per installed kilowatt hour than other melting techniques (see Table 5), it has distinct advantages. Success may be ascribed to its abilities to fuse any low-volatility material that undergoes a solid–liquid transition, and to maintain the fused condition for as long as is required to obtain the desired refining action. Production of high-quality refractory metals is possible, which is not the case with the other methods. Although investment and maintenance costs are high, they are compensated by increased quality.

The refining action in the electron-beam furnace may be classified into:

- 1) Removal of suboxides with high vapor pressures from their respective metals (i.e., NbO can be separated from Nb since their vapor pressure ratio at 2000 K is 10^3 , whereas that for TiO/Ti is 1)
- 2) Removal of interstitials such as nitrogen and hydrogen
- 3) Removal of oxygen by carbon as carbon monoxide
- 4) Removal of highly volatile metals from the metal to be melted and refined (e.g., removal of Cr and Fe from Zr)
- 5) Removal of insolubles from the melt material and of inclusions which float to the surface of the melt; since most materials to be processed are usually clean this contribution to refining is small

In addition to the usual refractory metals (V, Nb, Ta, Mo, W, Zr, Hf) which are normally melted and/or refined in electron-beam furnaces, beryllium, cobalt, uranium, nickel, and alloys such as special steels have also been melted. For example, the refining action during the melting of hafnium in an electron-beam furnace is far superior to that in vacuum arc melting. For technical data see Table 5.

For economic reasons titanium is mostly processed via vacuum arc melting, although electron-beam furnaces are also applied. The impurities oxygen, nitrogen, carbon, and iron remaining after refining lie in similar ranges for both processes, hydrogen values are, however, far lower for electron-beam melting. Ceramics (e.g., ZrO_2 and Al_2O_3), high-quality steels, and carbides of uranium, thorium, and zirconium are also melted in electron-beam furnaces.

Electron beams are also used for metallization, vacuum deposition, centrifugal casting, machining, and welding.

5.7. Fused-Salt Electrolysis Cells

Fused electrolysis can be classified both as a resistance electrothermal reactor and as an electrochemical reactor. It is not, however, a purely electrothermal reactor, and is therefore discussed separately from resistance furnaces.

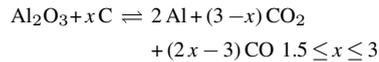
Due to their low reduction potentials elements such as aluminum, magnesium, and sodium cannot be recovered from aqueous solutions—hydrogen ions would be reduced in preference to these elements to produce hydrogen gas. Recovery of these elements by electrolysis can only be carried out in stable, non-aqueous electrolytes. In order to illustrate the technology of fused-salt electrolysis, two examples are described: the recovery of aluminum from alumina and sodium from sodium chloride. For magnesium electrolysis, see → Magnesium, Chap. 4.1.

Aluminum Recovery [76], [77], [87], [90–92]. The importance of aluminum electrolysis (→ Aluminum, Chap. 4.) is indicated by the 22.6×10^6 t of Al produced in 1998, with a power consumption of 14 MW · h/t (see Table 7).

The feed material for the production of aluminum is alumina (Al_2O_3). Due to alumina's

high melting point (2050 °C), fused-salt electrolysis of pure alumina is not economically viable. The Hall–Héroult process, developed at the end of the nineteenth century, permits electrolysis at 940–980 °C, this temperature is produced due to the resistance of the stable salt electrolyte based on the NaF– AlF_3 – Al_2O_3 system to the electric current. This electrolyte system has a sufficiently low liquid temperature and a high alumina solubility. Usually about 2–8% Al_2O_3 is dissolved in the cryolite-based (Na_3AlF_6) electrolyte. The density difference between the molten aluminum (ca. 2.3 g/cm³) and the molten electrolyte (ca. 2.1 g/cm³) is sufficiently large to ensure good separation of the molten electrolyte and molten aluminum.

The overall cell reaction for the electrolysis may be given as:



Usually the anode gas is a mixture of carbon dioxide and monoxide. Use of carbon anodes lowers the required electrical energy, at the expense of carbon anode consumption (ca. 0.4 kg C/kg Al).

At the normal current density (0.6–1.0 A/cm²) an additional anodic overpotential of ca. 0.5 V must be added to the theoretical potential of the above reaction (1.06–1.18 V at 977 °C) as well as a cathodic overpotential of about 0.5 V. This implies that the effective electrolysis potential or polarization potential is ca. 1.7 V. If the voltage drops across the electrodes, then electrolyte, conductors, and anode effects are included, the potential required for aluminum electrolysis lies in the range 3.9–4.6 V.

A typical electrochemical cell for the production of aluminum consists of:

- 1) A carbon-lined steel vessel (carbon blocks at the bottom of the furnace 40 cm deep)
- 2) Two rows containing a total of 16–24 consumable prebaked carbon anodes
- 3) Molten salt electrolyte (cryolite-based)
- 4) A liquid aluminum cathode
- 5) A layer (20–40 cm) of insulation (fire clay refractory) at the bottom of the furnace
- 6) Anode and cathode bus bars

In modern cells (Fig. 42) small amounts of alumina are fed between the two rows of sus-

pended anodes at frequent intervals. Crust breakers between the two rows of anodes break the frozen bath crust, a ventilation shaft removes the 5000–8000 m³/h of anode gas evolved per cell.

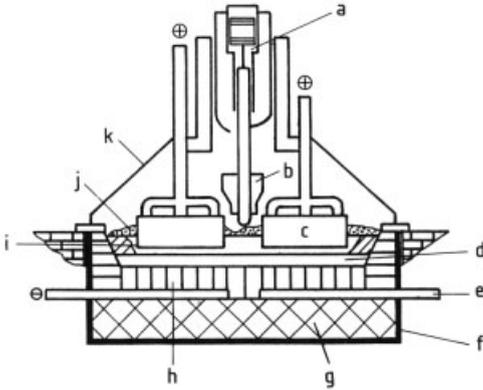


Figure 42. Typical Hall – Héroult aluminum production cell [76]

a) Charging system; b) Crust breaker; c) Graphite anodes; d) Molten aluminum; e) Bus bar; f) Steel container; g) Refractory; h) Graphite bottom (cathode); i) Molten electrolyte; j) Frozen electrolyte alumina crust; k) Cover hood

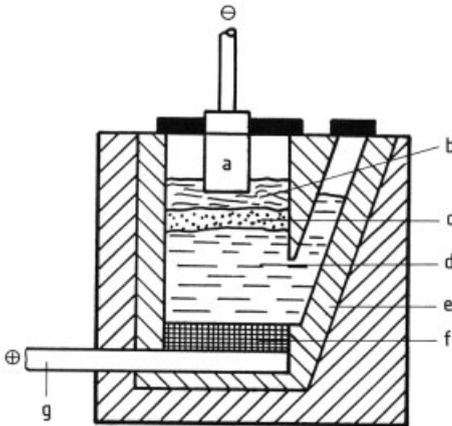


Figure 43. Typical aluminum refining cell [76]

a) Graphite cathode; b) High purity aluminum; c) Electrolyte; d) Anode alloy; e) Refractory; f) Carbon base; g) Anode bus bar

High-purity aluminum is produced in a refining cell [76]. This cell (Fig. 43) comprises the following elements:

- 1) A carbon base (f), which acts as the anode
- 2) An anode alloy (d) containing 30% copper (density at 750 °C 3.4–3.7 g/cm³) above the anode

- 3) An AlF₃–NaF–BaF₂–CaF₂-based electrolyte (c) (density 2.7–2.8 g/cm³) in the middle
- 4) High-purity molten aluminum (b) (density 2.3 g/cm³)

It is operated at a current density of 0.2–0.5 A/cm² and at a temperature of 750 °C, maintained by heat liberated due to the resistance of the electrolyte to the electric current.

Sodium Recovery [76]. Sodium is recovered from molten sodium chloride by fused-salt electrolysis in a Downs cell (Fig. 44); see also → Sodium. The salt is maintained in the molten state due to the resistance of the electrolyte to the electric current.

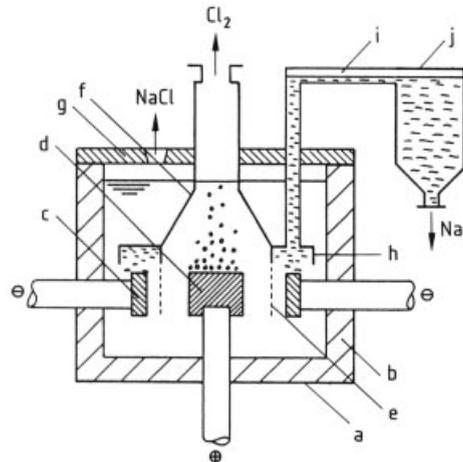


Figure 44. Downs cell for the production of sodium and chlorine from fused sodium chloride [76]

a) Steel container; b) Ceramic refractory; c) Iron cathode; d) Graphite anode; e) Diaphragm; f) Chlorine collection hood; g) Isolation lid; h) Collection bell for sodium; i) Sodium overflow; j) Sodium collector

The electrolyte is a molten mixture of BaCl₂, CaCl₂, and NaCl (*mp* ca. 600 °C). A cathode cylinder (c) is concentric with a graphite anode (d), the interelectrode gap being ca. 50 mm. A diaphragm (e) in the gap between the anode and cathode is attached to collection bells, allowing separate recovery of sodium and chlorine. Since sodium has a lower density (0.8 g/cm³) than the molten electrolyte (2.7 g/cm³), it drifts to the surface of the molten electrolyte where it is recovered in the collection bell.

These cells are typically run at current of up to 45 kA and potentials of 6.5–7 V, producing

about 800 kg sodium per day. Typical energy requirements lie between 9.8 and 10 kW · h/kg Na.

5.8. Modeling

The complex nature of the mass transfer processes taking place in electrothermal reactors makes it rather difficult to model them. However, fluid flow has been modeled using fundamental equations (e.g., Navier – Stokes), for example in Hall – Héroult aluminum recovery cells and in induction furnaces [96], [127], [128].

6. References

1. G. Johannsen, *Metall und Erz* **36** (1939) 325 – 333.
2. W. Heiligenstaedt: *Wärmetechnische Rechnungen für Industrieöfen*, Verlag Stahleisen, Düsseldorf 1951.
3. W. H. Duda: *Cement Data Book*, Bauverlag, Wiesbaden 1977, pp. 319 – 378.
4. K. E. Peray, J. J. Waddel: *The Rotary Cement Kiln*, Chemical Publishing Co., New York 1972, p. 1.
5. W. Flügge: *Statik und Dynamik der Schalen*, 3rd. ed., Springer Verlag, Heidelberg 1962.
6. R. Schardt, J. Steingaß, *Stahlbau* 1970, no. 3, 65 – 73; 1970, no. 5, 146 – 150.
7. J. Steingaß, Dissertation, TH Darmstadt, 1972.
8. H. Mettler, *Zem.-Kalk-Gips* 1969, no. 7, 306 – 311.
9. H. Mettler, Dissertation, RWTH Aachen, 1968.
10. V. Ramamurti, K. Raganatha Sai, *Zem.-Kalk-Gips* 1978, no. 9, 433 – 435.
11. K. Inove, T. Matsumoto, T. Ozaki, *Technical Review*, no. 73, Mitsubishi Heavy Ind., 1972.
12. H. Meedom, *Zem.-Kalk-Gips* 1976, no. 12, 568 – 571. I. Gulida, *Izv. Vyssh. Uchebn. Zaved Mashinost.* 1971, no. 8, 47 – 49.
13. C. Grinfeder, *Miner. Process.* (1968) no. 1, 14 – 19.
14. V. Ramamurti, L. S. Gupta, *Zem.-Kalk-Gips* 1978, no. 12, 614.
15. M. Garyk, M. Genda, *Zem.-Kalk-Gips* 1978, no. 9, 436 – 438.
16. E. Steinbiß, *Zem.-Kalk-Gips* 1976, no. 7, 321 – 328.
17. W. Bonn, B. Saxer, *Zem.-Kalk-Gips* 1978, no. 7, 329 – 332.
18. K. W. Liebler, *Zem.-Kalk-Gips* 1978, no. 7, 565 – 567.
19. H. Paulsen, *Zem.-Kalk-Gips* 1971, no. 5, 204 – 207.
20. H. Xeller, H. Jöhnk, *Zem.-Kalk-Gips* 1976, no. 12, 557 – 564.
21. G. Weislehner, *Zem.-Kalk-Gips* 1976, no. 10, 443 – 446.
22. W. Schroeble, *Zem.-Kalk-Gips* 1974, no. 2, 41 – 46.
23. H. Erni, *Zem.-Kalk-Gips* 1974, no. 10, 486 – 498.
24. G. Routschka, A. Majdic, *Zem.-Kalk-Gips* 1974, no. 10, 469 – 485.
25. G. Hotz, P. Bartha, *Zem.-Kalk-Gips* 1975, no. 6, 236 – 240.
26. M. Künnecke, H. Naefe, *Zem.-Kalk-Gips* 1969, no. 6, 271 – 275.
27. A. Künnecke, A. Kleinevoss, K. Wieland, *Zem.-Kalk-Gips* 1976, no. 7, 298 – 304.
28. G. Hotz, H. J. Schmidt, *Zem.-Kalk-Gips* 1976, no. 7, 305 – 307.
29. H. Barthel, *Zem.-Kalk-Gips* 1976, no. 7, 308 – 312.
30. R. Zengler, Dissertation, TU Clausthal, 1974.
31. F. W. Plank, *Zem.-Kalk-Gips* 1969, no. 75 – 81. T. Gori, F. Schwarzkopf, *Zem.-Kalk-Gips* 1978, no. 8, 392. S. Levine, *Pit & Quarry* 1977.
32. L. M. Ludera, *Zem.-Kalk-Gips* 1978, no. 12, 606 – 612.
33. *Handelsblatt, Westdeutsche Wirtschaftszeitung*, Düsseldorf, July 29, 1977.
34. G. A. Schroth, T. K. Diener, *Rock Prod.* (1976) 60 – 62, 64.
35. L. Kwech, *Zem.-Kalk-Gips* 1977, no. 12, 597 – 607. *Cement, Lime, Gravel* **49** (1974) no. 1, 3 – 6.
36. E. Bomke, *Zem.-Kalk-Gips* 1978, no. 12, 589 – 594.
37. K. Wilck, *Refra Colloquium* 1976.
38. G. K. Kapoor, *Zem.-Kalk-Gips* 1978, no. 12, 602 – 605. H. Ritzmann, *Zem.-Kalk-Gips* 1976, no. 5, 207 – 212. G. Hotz, *Refra Colloquium*, 1976.
39. H. Serbent, H. Krainer, *Techn. Mitt. Krupp, Forschungsber.* **23** (1965) 49 – 68.
40. Krakatau Steel: "Current Status of Coal-Based Direct Reduction for Iron Making," *Iron Making Technology Seminar*, Cilegon, Indonesia, May 7 – 9, 1990. G. Reuter, W. Schnabel, H. Serbent, *Stahl Eisen* **98** (1978) 1232 – 1237. *Ullmann*, 4th ed., **3**, 415 – 432.
41. G. Kossek, H. Lommert, H. Serbent, *Erzmetall* **32** (1979) 135 – 139.

42. H. Maczek et al., *Stahl Eisen* **96** (1976) 1233–1238.
43. K. Meyer, H. Pietsch, *Erzmetall* **27** (1974) 345–353.
44. A. Vaillant, H. W. Bodlaender, *Aufbereit. Tech.* (1972) no. 10, 631–638. G. Dumont, P. R. Belanger, *JEC Process Design & Development*, **17** (1978) no. 2, 107–114.
45. Kowa Seiko Pyrite Cinders Treatment Process, *Sulphur*, no. 83, July/Aug. 1969, 34–35, 38.
46. H. W. Gudenau, Eisenhüttenmännische Verfahrenstechnik Hochofen, TH Aachen.
47. L. V. Bogdandy, H. J. Engell: *Die Reduktion von Eisenerzen*, Verlag Stahl-Eisen, Düsseldorf 1967.
48. *Ullmann*, 4th ed., **3**, 395.
49. W. Weißbach: *Werkstoffkunde und Werkstoffprüfung* 1988, 9th ed., Vieweg, Wiesbaden.
50. *Ullmann*, 4th ed., **3**, pp. 395–432.
51. M. Hirsch, Verfahrenstechnische Merkmale des EOF-Stahlerzeugungsverfahrens, Lecture held at Lurgi-Maitagung, Frankfurt, May 21, 1986.
52. Korf Lurgi Steel Engineering, *Stahl Eisen* **110** (1990) no. 7.
53. Bernt Rollinger, *Handelsblatt*, no. **219**, Nov. 13, 1987
54. W. Borchers: *Die elektrischen Öfen*, Verlag von Wilhelm Knapp, Halle a.S. 1907.
55. K. Kegel: *Electroofentechnik in der Metallurgie*, VCH Verlagsgesellschaft, Weinheim 1988.
56. M. Orfeuil: *Electric Process Heating—Technologies/Equipment/Applications*, Batelle Press, Columbus Richland 1987.
57. G. Hoyle: *Electroslag Processes—Principles and Practice*, Applied Science Publishers, London 1983.
58. O. Winkler, R. Bakish (eds.): *Vacuum Metallurgy*, Elsevier, Amsterdam 1971.
59. R. Bakish: *Introduction to Electron Beam Technology*, John Wiley and Sons, New York 1962.
60. V. Dembovsky: Plasma Metallurgy—The Principles, *Material Science Monogr.* **23**, Elsevier, Amsterdam 1985.
61. S. M. L. Hamblyn: “Plasma Technology and its Application to Extractive Metallurgy,” *Min. Sci. Engng.* **9** (1977) no. 8, 151–176.
62. N. A. Barcza: “The Development of Large-scale Thermal Plasma Systems,” *J. S. Afr. Inst. Min. Metall.* **86** (1986) no. 8, 317–333.
63. *Ullmann*, 4th ed., **3**, pp. 519–542.
64. H. Walde: *Elektrische Stoffumsetzungen in Chemie und Metallurgie in energiewirtschaftlicher Sicht*, Klepzig Verlag, Düsseldorf 1968.
65. “Elektroofentechnik in der Metallurgie,” 19. *Metallurgische Seminar der Gesellschaft der Metallhütten- und Bergleute*, p. 130.
66. C. A. Otto: *Electric Furnaces*, George Newnes, Strand 1958.
67. J. H. Brunklaus, F. J. Stepanek: *Industrieöfen—Bau und Betrieb*, Vulkan-Verlag, Essen 1986.
68. A. K. Biswas, W. G. Davenport: *Extractive Metallurgy of Copper*, Pergamon International Library, Oxford 1976.
69. J. C. Yannopoulos, J. C. Agarwai (eds.): *Extractive Metallurgy of Copper—Pyrometallurgy and Electrolytic Refining. An International Symposium*, The Metallurgical Society of AIME, New York 1976.
70. P. Queneau (ed.): *Extractive Metallurgy of Copper, Nickel and Cobalt*, Interscience Publisher, New York 1961.
71. Rheinisch-Westfälisches Elektrizitätswerk AG, Elektrothermische Reduktion, company brochure, Essen 1985.
72. Rheinisch-Westfälisches Elektrizitätswerk AG, Elektroprozeßwärmeverfahren in der Industrie, company brochure, Essen 1991.
73. F. Denkhaus: “Herstellung hochreiner Stähle durch den Einsatz von Schrott beim Elektroschlacke-Umschmelzen,” Dissertation, RWTH Aachen 1987.
74. Durrer, G. Volkert, K.-D. Frank: *Metallurgie der Ferrolegierungen*, 2nd ed., Springer-Verlag, Berlin 1972.
75. V. P. Elyutin, Yu. A. Pavlov, B. E. Levin, E. M. Alekseev: *Production of Ferroalloys/Electrometallurgy*, 2nd ed., The Israel Program for Scientific Translations, Jerusalem 1961.
76. *Winnacker KÜchler*, 4th ed., **4**, Hansa, München 1986 p. 724.
77. F. Pawlek: *Metallhüttenkunde*, De Gruyter, Berlin 1983.
78. M. Rudolph, H. Schaefer: *Elektrothermische Verfahren—Grundlagen/Technologien/Anwendungen*, Springer-Verlag, Berlin 1989.
79. H. Bollinger, W. Teubner: *Industrielle Vakuumtechnik*, VEB Deutscher Verlag für Grundstoffindustrie, Leipzig 1980.

80. H. Wenzel: *Induktives Schmelzen und Warmhalten von Gußeisen*, RWE AG, Essen 1987.
81. J. Fasholz, G. Orth: *Induktive Erwärmung – Physikalische Grundlagen und technische Anwendungen*, RWE, AG, Essen 1991.
82. R. F. Baddour, R. S. Timmins: *The Application of Plasmas to Chemical Processing*, MIT Press, Massachusetts 1967.
83. D. Neuschütz: *Development of 3-phase a.c. Plasma Furnaces at Krupp*, *Iron Steel Eng.* **61** (1985), no. 5, 27–33.
84. M. Xu: “Massnahmen zur Erhöhung der Reduktionsgeschwindigkeit NE-metallhaltiger Schlacken,” Dissertation, RWTH Aachen 1991.
85. J. Höfler: “Reduktion NE-metallhaltiger Schlacken im Elektroofen unter besonderer Berücksichtigung der Verwendung gleichgerichteten Schmelzstroms,” Dissertation, RWTH Aachen 1988.
86. C. B. Gill: *Nonferrous Extraction Metallurgy*, Wiley & Sons, New York 1980.
87. P. C. Hayes: *Process Selection in Extractive Metallurgy*, Hayes Publishing Co., Brisbane 1985.
88. H. W. Gudenau: *Eisenhüttenmännische Verfahrenstechnik*, Institut für Eisenhüttenkunde, Aachen 1985.
89. E. Decker: “Rationeller Einsatz von Elektrowärme in der Metallindustrie,” *VDI-Fachtagung: Rationelle Energieanwendung in der Industrie*, Essen 1981.
90. K. Grjotheim et al.: *Aluminium Electrolysis – The Chemistry of the Hall-Heroult Process*, Aluminium-Verlag GmbH, Düsseldorf 1977.
91. K. Grjotheim, H. Kvande: *Understanding the Hall-Heroult Process for Production of Aluminium*, Aluminium-Verlag GmbH, Düsseldorf 1986.
92. K. Grojtheim, B. J. Welch: *Aluminium Smelter Technology – A Pure and Applied Approach*, Aluminium-Verlag GmbH, Düsseldorf 1980.
93. E. Höffken, F.-J. Strunck, J. Wendorff, J. Wolf: “Das Edelstahlwerk der Thyssen Stahl AG in Oberhausen und seine Entwicklung von 1979–1987,” *Stahl Eisen*, **108** (1988) no. 6, 281–288.
94. K.-H. Brokmeier: *Induktives Schmelzen*, Verlag W. Girardet, Essen 1966.
95. *Proceedings of “Junker-Ofentagungen,”* Otto Junker GmbH, Lammersdorf.
96. *Proceedings of “Light Metals,”* The Minerals and Metals Society, Warrendale, Pa.
97. G. Rath: “Der Elektroreduktionsofen – Ein Aggregat für die Nichteisenmetallurgie,” *Erzmetall* **43** (1990) 81–85.
98. G. N. Angelopoulos, S. H. Pavlou, D. C. Papamantellos: “Ferronickel,” *Erzmetall* **42** (1989) 107–113.
99. H. Nakamura, S. Hirakawa, E. Nomura: “Electrothermal Slag-fuming Process and Zinc Leach Residue Treatment by Lead Blast Furnace at Kamioka Smelter,” *TMS Paper Selection*, A 77–9, The Metallurgical Society of AIME, New York 1977.
100. H. P. Rajcevic, W. R. Opie: “Development of Electric Furnace Slag Cleaning at a Secondary Copper Smelter,” *J. Met.* **34** (1982) March, 54–56.
101. P. F. Feri, A. Perillo: “The New Lead Smelter of Portovesme,” *Extraction Metallurgy ‘85*, The Institute of Mining and Metallurgy, London 1985.
102. T. P. Battle, J. P. Hager: “Viscosities and Activities in Lead-Smelting Slags,” *Metallurgical Transactions B*, **21B** (1990) 501–510.
103. W. P. Channon, R. C. Urquhart, D. D. Howat: “The Mode of Current Transfer Between Electrode and Slag in the Submerged-Arc Furnace,” *J. S. Afr. Inst. Min. Metall.* **74** (1974) no. 8, 4–7.
104. G. P. Tyroler, C. A. Landolt (eds.): *Proceedings of Extractive Metallurgy of Nickel and Cobalt*, Warrendale, Pa., 1988.
105. *Proceedings of Symposium Nickel*, GDMB, Clausthal-Zellerfeld, Sept. 24–25, 1970.
106. D. J. I. Evans, R. S. Shoemaker, H. Veltman (eds.): *Proceedings of Laterite Symposium*, AIME, New York 1979.
107. T. S. Mackey, D. Prengaman (eds.): *Proceedings of Lead-Zinc ‘90*, TMS, Warrendale 1990.
108. W. G. Davenport, E. H. Partelpoeg: *Flash Smelting-Analysis, Control and Optimization*, Pergamon Press, New York 1987.
109. H. Brod, F. Kempkens, H. Strohschein: “Energierückgewinnung aus einem UHP-Elektrolichtbogenofen,” *Stahl Eisen* **109** (1989) 229–238.
110. K. Rüdinger: “Erschmelzen von Titan im Lichtbogenvakuumofen,” *Metall* **42** (1988) 774–779.
111. D. Meredith et al., “Der neue Gleichstrom-Lichtbogenofen bei der Florida

- Steel Corporation," *Stahl Eisen* **108** (1988) 796–800.
112. "Stahl & Eisen," *Jahrbuch Stahl 1991*, Verlag Stahleisen mbH, Düsseldorf 1990.
 113. E. Decker: "Energiebedarf und Wirtschaftlichkeit beim Schmelzen von Gußeisen in Kupol- und Induktionsöfen," *Elektrowärme International* **38** (1980) B 2, 92–97.
 114. A. Dickopp: "Überblick über elektrisch beheizte Anlagen zum Feuerverzinken von Stahlteilen," *Elektrowärme International* **32** (1974) B 3.
 115. E. Decker, A. Dickopp: "Energieeinsatz und Wärmerückgewinnung beim Schmelzen von Aluminium," *Aluminium* **57** (1981) 3.
 116. E. Decker, A. Dickopp: "Induktionstiegelöfen für sinnvolle Energieausnutzung in der Eisengießerei," *Maschinenmarkt* **87** (1981) 30.
 117. H. Ronig: "Induktionsöfen für das Warmhalten und Vergießen von Leichtmetall," *Metall* **37** (1983) no. 5, 459–465.
 118. D. Hartmann, H. Rohn: "Der Netzfrequenz-Induktions-Tiegelofen zum Schmelzen von Nichteisen-Schwermetall-Legierungen," *Zeitschr. Metallkunde* **48** (1957) no. 3, 85–90.
 119. *Conference Proceedings of the "International Conference on Vacuum Metallurgy"*, Tokyo 1973, München 1982, Linz 1985.
 120. C. W. Chang, J. Szekely: "Plasma Applications in Metals Processing," *J. Met.* **34** (1982) Feb. 57–64.
 121. F. Esser, H. Fiedler, W. Lachner: "Zur Theorie des Ein- und Niederschmelzen festen, metallischen Einsatzguts in Plasmaöfen – ein Beitrag zur Verfahrensoptimierung des Plasmaprimaryschmelzens," *Neue Hütte* **19** (1974) no. 10, 577–586.
 122. *Proceedings 8th International Conference on Vacuum Metallurgy*, Linz, Austria, 1985.
 123. "A world first – The DC plasma arc furnace," *The S. Afr. Mechanical Engineer* **39** (1989) no. 5, 223–228.
 124. S. Lavoit, C. Dubé, G. Dubé: "The ALCAN Plasma Dross Treatment Process," *Light Metals 1991*, E. L. Rooy (ed.): The Minerals and Metals Society (1990) 981–985.
 125. SKF, Publications and brochures on PLASMARED, Landskrona, Sweden.
 126. H. H. Kellog in N. J. Themelis, P. F. Duby (eds.): *International Symposium on Quantitative Description of Metal Extraction Processes*, The Minerals, Metals & Materials Society, Warrendale 1991.
 127. J. Szekely: "The Role of Mathematical Models in New Process Development," in M. Koch, J. C. Taylor (eds.): *Productivity and Technology in the Metallurgical Industries*, The Minerals, Metals & Materials Society, Warrendale 1989, pp. 105–143.
 128. J. Szekely: "The 1987 Extractive Metallurgy Lecture," *Met. Trans.* **19B** (1988) 525–540.
 129. G. K. Bhat (ed.): *Proceedings of the Conference "Special Melting and Processing Technologies"*, San Diego, CA, Noyes Publications, New Jersey 1989.
 130. A. Choudhury: *Vacuum Metallurgy*, ASM International, 1990.
 131. Mannesmann Demag Hüttentechnik, Brochure, Duisburg, Germany.
 132. P. Hanniala, T. Mäkinen, M. Kytö: "Flash Technology for Converting," in J. Vereecken (ed.): *EMC '91: Non-Ferrous Metallurgy – Present and Future*, Elsevier Science Publishers Ltd., New York 1991, pp. 191–203.
 133. Rheinisches-Westfälisches Elektrizitätswerk AG, Inductive Erwärmung, company brochure Essen 1991.
 134. T. S. Mackey, R. D. Prengaman (eds.): *Lead – Zinc '90*, TMS, Warrendale 1990, pp. 453–528.
 135. J. Dutrizac, V. Ramachandran, A. Gonzales: *Lead – Zinc 2000*, TMS, Warrendale 2000.
 136. J. K. Brimacombe, A. P. Watkinson, *Metall. Trans. B* **9B** (1978) 201–219.
 137. P. V. Barr, J. K. Brimacombe, A. P. Watkinson, *Metall. Trans. B* **20B** (1989) 391–419.
 138. A. P. Watkinson, J. K. Brimacombe, *Metall. Trans. B* **13B** (1982) 369–378.
 139. V. Venkateswaran, J. K. Brimacombe, *Metall. Trans. B* **8B** (1977) 387–398.
 140. J. D. Mc Cain, J. M. Floyd (eds.): *Converting, Fire Refining and Casting*, TMS, Warrendale 1993.
 141. W. J. Chen, C. Diaz, A. Lurashi, P. J. Mackey (eds.): *Pyrometallurgy of Copper*, **Vol. IV, Copper 95**, CIM 1995.
 142. G. A. Eltringham, N. L. Piret, M. Sahoo (eds.): *Plenary Lectures, Copper '99*, TMS, Warrendale 1999.
 143. D. B. George, W. J. Chen, P. J. Mackey, A. J. Weddick (eds.): *Smelting Operations and Advances, Copper '99*, TMS, Warrendale 1999.
 144. D. B. George, J. C. Taylor (eds.): *Copper Smelting – An Update*, TMS, Warrendale 1981.

145. J. K. Brimacombe, P. J. Mackey, G. J. W. Kor, C. Bickert, M. G. Ranade (eds.): *Savard/Lee International Symposium on Bath Smelting*, TMS, Warrendale 1992.
146. K. Tozawa (ed.): *Zinc "85"*, MMIJ, Sendai, Japan 1985.
147. J. Dutrizac, J. A. Gonzales, G. L. Bolton, P. Hancock (eds.): *Zinc and Lead Processing*, CIM, Montreal 1998.
148. J. Dutrizac, V. Ramachandran, A. Gonzales (eds.): *Lead-Zinc 2000*, TMS, Warrendale 2000.
149. A. K. Biswas, W. G. Davenport: *Extractive Metallurgy of Copper*, 3rd ed., Pergamon, 1994.
150. K. Krone: *Aluminium-recycling*, Vereinigung Deutscher Schmelzhütten e.V., Düsseldorf 2000.
151. Intensivierung metallurgischer Prozesse, 37. Metallurg. Seminar, Heft 87, Schriftenreihe der GDMB, Clausthal-Zellerfeld 2000.
152. J. A. Asteljoki, R. L. Stephens (eds.): *Sulfide Smelting 98/Proc. Symp.*, TMS, Warrendale 1998.
153. R. G. Reddy, R. N. Weizenbach, C. A. Landolt (eds.): *Extractive Metallurgy of Copper, Nickel and Cobalt*, TMS, Warrendale 1993.
154. K.-H. Heinen: *Elektrostahlerzeugung*, 4. ed., Stahl & Eisen, Düsseldorf 1997.
155. R. Bakish (ed.): *Proc. Conf. Electron. Beam Melting and Refining*, Bakish Materials Corp., Englewood, NJ 1997.
156. S. Schiller, U. Heisig, S. Panzer: *Electron Beam Technology*, J. Wiley & Sons, New York 1982.
157. Schlacken in der Metallurgie, Heft 83, Schriftenreihe der GDMB, Clausthal-Zellerfeld 1999.