Chapter 4

Ferroalloys Processing Equipment

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Chapter Outline

4.1 INTRODUCTION TO FERROALLOYS PROCESSING TECHNOLOGY

The process by which ore is converted to a ferroalloy contains a number of steps. These include mining the ore, preparing the ore by processes such as crushing, screening, washing, grinding, or milling, and sometimes applying

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FIGURE 4.1 General view of a ferroalloys smelter. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd).*

beneficiation processes such as flotation, followed by smelting and refining. A general view of a ferroalloys smelter is shown in Figure 4.1.

Raw material is delivered to the smelter from the mine in bulk by rail, road, or sea. The raw materials required for ferroalloy smelting include the ore, reductants, and fluxing materials. These materials are delivered to a raw materials storage facility. Granular materials may be stored in an open stockpile or a bunker, from where they are retrieved and transferred by means of belt conveyors. Fine powdered materials are conveyed in pneumatic conveying systems. In a plant with multiple furnaces, there is generally a common bulk storage facility, with an arrangement of incline conveyers, shuttle conveyors, transfer conveyors, or skip hoists and intermediate bins to deliver material to the furnaces in the correct proportions at appropriate times. Feed bins containing the correct feed recipe are situated above the furnace roof. Where charging cars are used, the bins may be further from the furnace.

The smelting process may include preheating, prereduction, sintering, and pelletizing of the material prior to its introduction into the furnace. These processes receive feed material from the raw material handling facility and deliver processed material into the furnace. In larger furnaces, the raw material is fed into the furnace through feed chutes set into the roof, which facilitate the delivery of the material to a specific region of the furnace. In smaller furnaces, charging cars are often used for this purpose.

Irrespective of whether the furnace is circular or rectangular, AC or DC, the furnace shell is composed of a steel structure consisting of a base, sidewall, and roof. The base and shell are lined with refractory material to form a crucible, whereas the roof may be constructed of refractory material or may be of water-cooled steel or copper construction. The hearth is commonly cooled by forcing air across it by means of a dedicated fan. The sidewalls may rely on natural convection for cooling, or they may be cooled by forced air convection or by one of several different water-cooling methods, depending on the required intensity of heat removal. The simplest of these is film cooling, where a water film runs down the outside of the steel shell. Spray cooling systems provide additional cooling by spraying jets of water onto the shell. Copper cooling elements with integral water passages provide the greatest intensity of water cooling. The copper cooling elements are set into the refractory lining. In these closed water circulation systems, the returning hot water is cooled in an indirect heat exchanger to avoid contamination of the cooling water. The cooling water system has its own pumps and ancillary equipment, and it may be fitted with an emergency water supply system, as a loss of cooling water to a furnace has potentially catastrophic consequences.

Electric current is introduced into the furnace by means of carbon electrodes, which receive power at relatively low voltage and high current from a voltage step-down arrangement connected to a high voltage (HV) supply. The electrodes are individually supported on a clamping mechanism, which allows the electrodes to be lowered into the furnace and additional sections added as they are consumed by the process. The contact shoes and bus bars through which current is supplied to the electrodes may be water cooled and may be connected to the same cooling water system as the furnace sidewalls.

Exhaust gas leaves the furnace through a duct, where it is cooled and the particulate matter removed prior to flaring to atmosphere. Waste heat boilers and other energy recovery systems placed downstream of the furnace are becoming increasingly common components of smelting plants.

Metal and slag may be tapped from a single tap hole, or there may be dedicated slag and metal tap holes opposite each other in the furnace, the slag tap holes usually being at a higher elevation than the metal tap holes. After metal is tapped from the furnace, it may be granulated, cast, or further refined. Slag from ferroalloy processes may be further processed to extract entrained metallic particles prior to being discarded. Some slags are suitable for use as aggregates for concrete.

In the following sections of this chapter, the equipment used for the smelting of ferroalloys will be described. Section 4.1 describes furnace technology and operations, whereas Section 4.2 discusses the more important processing steps, which may be applied to the raw materials at the smelter prior to their smelting in the furnace. Hydrometallurgical processes such as the concentrating of nickel ores are not included. Section 4.3 describes the treatment of the product and slag after it leaves the furnace, and Section 4.4 deals with other furnaces for ferroalloys production.

4.1.1 Ferroalloys Basic Furnace Design and Operation

The smelting of ferroalloys is commonly performed in electric arc furnaces. Although ferromanganese can be produced in a blast furnace in a manner similar to iron, the reduction of chromium and silicon from their oxides requires higher process temperatures and lower oxygen potentials than can be achieved in a blast furnace. To create the required high temperature and low oxygen environment, carbon electrodes are inserted into a mixture of ore, flux, and carbon reductant in an electric arc furnace. The low-voltage, high-current arcs at the electrode tips create a zone of high temperature and low oxygen potential. No oxygen is blown into the furnace for the purpose of raising the temperature. Radiation from the arc zone impinges directly on the feed material, allowing the efficient transfer of energy from the arc to the feed material. As the arc is considerably shorter than that of an open-arc furnace, the bulk of the energy is transferred to the feed material by resistance (Joule) heating due to the flow of electric current through the furnace contents. Oxygen from the metal oxide combines with the carbon in the feed material to form carbon monoxide, liquid metal, and slag. An electric furnace operating in this manner is called a submerged arc furnace. A photograph of a furnace in operation showing the electrodes passing into the furnace charge is shown in Figure 4.2.

In submerged arc processes, there is no visible arc. The electrode is immersed in the solid raw material with its tip immersed in the slag. The coke in the feed mix passes down into the slag, where reduction of oxides occurs as the molten slag mixes with the coke. Heating is predominantly due to the resistance of the slag, although some arcing may occur between the electrodes and the coke bed. In processes where a slag is not formed, such as ferrosilicon smelting, a short visible arc may exist. In a slag resistance furnace, the tip of the electrode protrudes into the slag, there is no arc, and the heat transfer is by joule heating. Raw material melts as heat is transferred from the slag with which it is in contact.

Submerged arc furnaces, although they all operate on the same general principles and use similar equipment, differ in the details of their construction and operation. The possible variations in a number of the important furnace parameters are summarized in Table 4.1. However, the geometrical, electrical, and other parameters for a furnace for a particular application are dictated by the requirements of the process. Consequently, the variation in design between individual ferrochrome furnaces, for example, is relatively small, but silicon metal furnaces, for example, may differ substantially from ferrochrome furnaces in the details of their construction and operation. This also holds for small furnaces usually operating in resistance heating mode (arc-less) and used for refining operations.

FIGURE 4.2 The furnace in operation showing the electrodes passing into the furnace charge. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

TABLE 4.1 Furnace Parameters

Parameter	Options
Overall shape	Circular or rectangular
Power supply	AC or DC
Arc type	Open, submerged, shielded, brush, resistance (no arc)
Number of electrodes (AC furnaces)	Single phase: 2 Three phase: 3, 6 (three pairs), 6 (2 × 3)
Number of cathodes (in DC furnaces)	1, 2
Roof	Gas-tight (hermetic), semiclosed, open
Sidewall cooling	Natural convection, forced air convection, water film cooling, water spray cooling, water-cooled copper elements

The design of an AC submerged arc furnace is based on the electrical power required to produce the required tonnage of ferroalloy. The required tonnage of alloy per year is decided based on the available ore and other economic factors. The specific energy requirement (SER) of the process (in kWh/ton) is determined by the process and the ore characteristics and is usually obtained by calculating a mass and energy balance. Representative figures for various processes are provided in Table 4.3 (presented later). When the SER is known, and the required annual alloy production is known, the power (MW) rating of the furnace is determined by multiplying the kWh per ton by the number of tons per hour. Once the power (MW) rating of the furnace is known, the other parameters may be determined. Important considerations in the sizing of the furnace are the required electrode resistance and current. A number of empirical methods have been developed to describe the relationship between the various parameters such as electrode diameter and furnace resistance.

4.1.1.1 Kelly's Method

The relationship between the electrode diameter and the furnace resistance is characterized by empirical formulas (Andreae, 1935 and 1950) and refined by Kelly (1958). These researchers found that the furnace resistance is inversely proportional to the electrode diameter:

$$k = \frac{E\pi D}{I} \tag{1}$$

where k = electrode periphery resistance, E = electrode-to-ground voltage, I = current per electrode, and D = electrode diameter in inches.

TABLE 4.2 Typical "*k*" Factors for Submerged Arc Operations (Kelly, 1958)

Product	Typical *k* Factor
Phosphorus	0.75–1.0
HC FeCr (Low Si)	0.35–0.65
HC FeCr (High Si)	0.2–0.3
50% FeSi	0.24–0.34
CaC_2	0.19–0.22
75% FeSi	0.16–0.2
FeCrSi	0.12–0.17
SiMn	0.1–0.15
FeMn	0.08–0.13

The proportionality constant *k* became known as the Kelly factor (Kelly, 1958). This factor is dependent on the process and the size of the furnace. Kelly factors have been published for a variety of furnace configurations. The values published by Kelly are included in Table 4.2. Due to the many economic changes that have taken place since the publication of Kelly's paper, the actual values of the Kelly factor have been adjusted somewhat from those originally calculated in order to match the performance of much larger furnaces and new feedstocks (Barker, 2011). The Kelly factor is most often used when scaling up or down from a known operation.

Using equation (1), an initial estimate is made of the electrode diameter, electrode current and electrode voltage. The electrode size is also dependent on the anticipated current density that can be carried by the electrode. This is determined by experience based on the electrode type and the process. The choice of an appropriate value of the electrode-to-ground voltage is informed by the performance curve of the transformer.

The expected power factor $cos(\varphi)$ of the furnace is estimated, based on operating knowledge of other furnaces for this process. The power factor is largely determined by the process and the details of the placement of the major current-carrying components such as the electrodes and bus bar bundles. The furnace MVA rating may then be determined.

4.1.1.2 Westly's Method

Westly (1974) developed a different approach to sizing furnaces and determining favorable electrical operating conditions. This method finds greatest acceptance in slagless (flux-less) processes such as silicon metal and FeSi production. Based on the performance of operating furnaces, he showed that

$$I_{el} = C_3 P^{2/3} \tag{2}$$

where I_{el} is the electrode current in kA, C_3 is the factor appropriate to the particular smelting process, and P is the total power (VA) rating of the three-phase furnace in MVA. For example, for a ferroalloy process with 75% Si, a typical value of C_3 is approximately 10.5. The optimum electrode current for a 30 MVA furnace producing a 75% Si product would be thus $I_{el} = 10.5 \cdot 30^{2/3} = 101.4$ kA. From equation (2), the electrode-to-bath (phase) voltage in kV can be derived as

$$V_{ph} = \frac{\sqrt[3]{P}}{3\ C_3} \tag{3}$$

Thus, for the same case phase voltage would be $V_{ph} = 30^{1/3}/(3 \cdot 10.5) = 0.0986$ kV = 98.6V. Westly's method has similarities to the method described in detail next.

4.1.1.3 Method by Gladkih et al.

An example of parameters used for selection at some European (Russia, Ukraine) and Asian (Kazakhstan, China) ferroalloys plants is shown in Table 4.3 (Gladkih et al., 2007). Note that other values might be reported (for example, specific energy demand might be lower if charge preheating or prereduction is used), but the procedure of furnace system design remains similar.

First, the required transformer power (in kVA) is calculated:

$$P = \frac{G \cdot A}{24 \cdot K \cdot \cos(\varphi)} \tag{4}$$

where G is the desired furnace productivity for the alloy, t/day, A is the specific energy demand (SER), kWh/t alloy (Table 4.3), and K is the repair time correction factor, accounting for plant availability (usually adopted as ~0.94 ± 0.01, meaning ~6% of the year time is allowed for furnace repair and maintenance). The power factor $cos(\varphi)$ is first adopted as 0.84 ± 0.02. Then the product $cos(\varphi) \cdot \eta_{el}$ is selected from the table, taking into account that higher transformer power usually leads to lower $cos(\varphi) \cdot \eta_{el}$ product values. The electrical efficiency η_{el} is normally in the range 0.84 to 0.90 (again, higher efficiency is selected for lower power systems).

The active furnace power (kW) is then estimated:

$$P_{act} = P \cdot \cos(\varphi) \cdot \eta_{el} \tag{5}$$

and the nominal phase voltage (V) is determined per one electrode:

$$V_{ph} = C \cdot (P_{act}/k_{el})^n, \tag{6}$$

where C is the coefficient in Table 4.3, which depends on the material, process type, and electrical regime of the smelting, and k_{el} is the number of the

TABLE 4.3 Parameters for Ferroalloys Furnace Design*

Ferroalloy Type	Product $cos(\varphi) \cdot \eta_{el}$	SER, *A*, kWh/t alloy	Process Parameter *C*		Electrode Factor *EP*	Nominal Current Density *j*, A/cm^2
			Flux	Flux-less		
18% Si	0.70–0.68	2000–2200	—	3.0–3.1	1.42–1.99	7.0
25% Si	0.71–0.69	2700–2800	—	3.05–3.15	1.43–1.99	7.0
45% Si	0.72–0.70	4700–4900	—	3.2–3.3	1.50–2.00	7.0
65% Si	0.73–0.71	7400–7700	—	3.35–3.40	1.57–2.02	7.0
75% Si	0.74–0.72	8800–9200	—	3.4–3.5	1.60–2.03	7.0
90% Si	0.76–0.74	12 500–13 500	—	3.5–3.7	1.65–2.04	8.4
CaC_2	0.72–0.70	2500–3000	—	3.0–3.5	1.44–1.50	6.8
FeSiCa	0.68–0.66	12 000–13 000	6.7–7.7	—	1.34–1.41	12.0
HC FeMn	0.68–0.65	3800–4100	7.3–8.3	—	1.54–1.49	7.6
HC FeCr	0.75–0.73	3450–3600	8.0–8.6	—	1.44–1.50	7.6
FeSiMn	0.69–0.67	4100–4700	5.7–6.7	—	1.34–1.41	7.6
FeSiCr	0.72–0.70	6200–6500	7.2–7.4	—	1.53–1.72	7.6

**When a range is shown, the lower limit is for lower power and the higher limit is for high power furnaces.*

electrodes in the furnace (3 or 6). The n value is 0.25 for flux processes (high amount of slag—volumetric power distribution) and 0.33 for flux-less processes (low or no slag—surface power distribution).

Once a calculation like the preceding one has been performed or an appropriate Kelly's factor has been chosen, an initial estimate can be made of the electrode current and consequently the electrode diameter. The relationship between electrode diameter and electrode current is based on the properties of the carbon electrodes to be used. The current in the electrode (kA) is determined as follows:

$$I = \frac{P_{act}}{3 \cdot V_{ph}\, k_{el}} \tag{7}$$

and the calculated electrode diameter (mm) is determined as follows:

$$d_{calc} = \frac{EP \cdot I}{V_{ph}} \tag{8}$$

where the EP factor is selected from Table 4.3. The calculated diameter is usually rounded up to the nearest number as multiples of 50. The check of the calculation's consistency is made by evaluating the product $cos(\varphi) \cdot \eta_{el}$ with the formula:

$$\cos(\varphi) \cdot \eta_{el} = \frac{1}{\sqrt{R^2 + X^2}} \cdot \frac{R^2}{R + r} \tag{9}$$

where R (ohm) is the active resistance of the furnace hearth, r (ohm) is the active resistance of the short circuit impedance of the supply network ("short net"), and X (ohm) is the total reactive resistance of the furnace circuit. Values of r commonly vary from 0.2 mOhm for low power transformers (<17 MVA) to 0.14 for higher power (33 to 63 MVA). Values of X, respectively, vary from 1 to 0.8 mOhm (depending on the transformer and the network short circuit fault rating characteristics). The product calculated by equation (8) should not deviate more than ±5% from the value adopted at the beginning of calculations; otherwise the calculation should be iterated once more.

The furnace diameter is determined by the required hearth power density, which is calculated by dividing the MW rating of the furnace by the surface area of the hearth. An appropriate value of this variable for a particular furnace is selected based on experience in other furnaces for this process and the desired sidewall cooling method. The pitch circle diameter of the electrodes and the electrode-to-wall distance are two other important furnace dimensions, the selection of appropriate values for which is based largely on experience of similar furnaces. For example, the distance between the lining and electrode is close to the electrode diameter value, but it can be ±20% more or less depending whether the process is flux or flux-less, whether the furnace is rotated, and so on. The diameter of the hearth similarly is close to the pitch diameter plus three times electrode diameter, again also higher or lower by ±30% versus process type and furnace design.

In the case of DC furnaces, the Kelly factor plays no part because electrode resistance is determined almost entirely by the length of the open arc and is process independent. The DC electrode current circuit has no inductive reactance and the furnace power factor is a function only of the rectifier design and operating point. The values of parameters such as the hearth power density and the electrode current density also differ significantly from those used for AC furnaces (Barker, 2011).

4.1.2 Ferrochrome, Ferrosilicon, Ferromanganese, and Silicomanganese Furnaces

Traditionally, smelting furnaces have been three-phase AC furnaces, although DC furnaces are increasing in popularity. The most common furnace type for ferrochrome (FeCr), ferrosilicon (FeSi), ferromanganese (FeMn), and silicomanganese (FeSiMn or SiMn) is a circular AC furnace with three electrodes arranged in a triangular configuration. Electric current is introduced into the furnace by three electrodes. The electrodes receive power from a single three-phase transformer or three single-phase transformers. Figure 4.3 shows a photograph of the inside of a ferrochrome furnace shell taken during construction. The lining and the electrodes are visible.

The base of the shell is usually flat and may be welded or bolted to the cylindrical section. The shell holds the refractory lining together and provides a certain degree of resistance to thermal expansion of the crucible.

These ferrochrome, ferromanganese, ferrosilicon, and silicomanganese furnaces employ a carbon lining in contact with the molten metal on the hearth and sidewalls, with various grades of aluminosilicate bricks used to form an insulating lining between the carbon and the shell. In the slag zone, the lining

FIGURE 4.3 Circular AC ferrochrome furnace showing the lining and electrodes. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

may include graphite tiles bonded to the shell to provide a thermally conductive layer between the bricks and the shell, with carbon bricks and aluminosilicate bricks on the hot face. The carbon lining may be made of large carbon blocks, which are machined to fit together. A thick layer of carbon ramming material may be used instead, as the cost is lower, but carbon ramming is generally less resistant to wear. The freeboard region above the slag is usually made of less expensive aluminosilicate bricks, as the conditions are generally less severe. The furnace lining shown in Figure 4.4 is a typical ferroalloy furnace refractory lining.

The furnace crucible is designed to maintain a balance between retaining sufficient heat to maintain the desired temperatures in the crucible, limit the heat losses from the furnace, and maintain a safe refractory and shell temperature. To achieve this balance, the shell may be cooled. Water and air are the most common cooling media, although oil may also be used. The use of oil carries a fire risk, however. The shell floor plates are supported on a set of steel rail sections or I-beams resting on the foundation, which consists of reinforced concrete plinths spaced at intervals to allow forced air cooling of the floor plates. Water is not used to cool the hearth because of the explosion risk associated with contact between water and liquid metal or slag. The simplest application of cooling water on the sidewall of the furnace is in the form of a water film on the outside surface of the shell. Water is poured or sprayed onto the shell near the top of the wall and runs down the shell into a channel welded to the lower shell. Channel cooling, in which water is pumped through channels welded to the shell, provides an enhanced capacity for heat removal. The cooling water circuit is a closed system containing treated water. Water is cooled in a heat exchanger or cooling tower. There is often an emergency

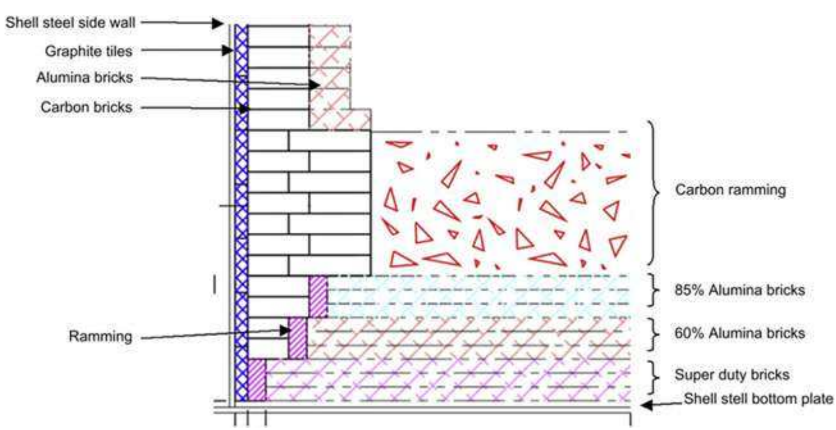

FIGURE 4.4 Section through the lining of a typical ferroalloy furnace. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

cooling water system, which is activated in the event of failure of the pumps or other components of the cooling system, in order to prevent excessive temperatures on the furnace.

The furnace roof is exposed to high temperatures and heat loads. The roof is built of water-cooled steel sections, where the cooling water pipes or passages form part of the structure. As ferroalloy smelting processes produce carbon monoxide and other noxious gases as by-products of the reduction process, the furnace roof may be made as gas tight as possible to contain this noxious gas. The furnace is operated under a small negative pressure to prevent leakage of gas. These closed roofs are common in ferrochrome furnaces, where the closed design reduces the hexavalent chrome (Cr^{6+}) content of the dust emissions in addition to preventing the release of carbon monoxide. A seal, typically made of sand, is fitted between the top of the shell and the furnace roof to provide a gas-tight seal. A closed roof for a ferrochrome furnace is shown in Figure 4.5. In this design, the cooling water pipes contribute to the structural strength of the roof.

A semiclosed roof on a FeCr furnace is shown in Figure 4.6. The roof panels are of water-cooled steel. The openings in the roof provide access for manual charging of raw material into the furnace. A small negative pressure is maintained in the exhaust gas system attached to the roof structure to assist with removal of gases and fumes, preventing leakage of these fumes into the building.

The feed system delivers raw materials and reductants to the furnace in the correct proportions. These systems may vary in complexity from simple manual systems in which batches of material are measured manually and delivered to a bin, from where the mix is fed into the furnace using wheelbarrows or a small front end loader, to fully automated systems of bins with

FIGURE 4.5 Closed roof on a FeCr furnace. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

FIGURE 4.6 Semiclosed roof on a FeCr furnace. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

weighing systems and automatic feeders. Most modern furnaces employ some level of automation in their raw material handling and batching processes.

Ore and reductants are delivered to a raw materials storage facility. Granular materials may be stored in an open stockpile or a bunker, from where they are retrieved and transferred by means of belt conveyors. In a plant with multiple furnaces, there is generally a common bulk storage facility, with an arrangement of incline conveyers, shuttle conveyors, transfer conveyors, or skip hoists, and intermediate bins to deliver material to the furnaces in the correct proportions at appropriate times. Screens may be fitted to the bins to prevent ingress of oversized particles or excessive fine particles.

Raw materials are conveyed from the storage area to day bins above the furnace. Electromagnets may be installed above the conveyors to remove tramp iron. A sampling system may remove samples of feed material for analysis. Each day bin is dedicated to a specific raw material. The material is drawn from the day bins by means of vibrating feeders, which discharge into weigh hoppers to facilitate the preparation of the required blend of material. Conveyors transfer blended material to the feed bins above each furnace.

Where furnace feed material is preheated, it passes from the day bins into the preheaters, which replace the feed bins. The preheaters are thermally insulated. Two types of preheating systems are in use. In the single rotary preheater, the feed material is fed into segments of the preheater in sequence. The outlet of each segment is connected to the feed chutes of a sector of the furnace. In a multiple preheater arrangement, each preheater forms an individual furnace feed bin, feeding a particular sector of the furnace. Feed material for ferrochrome is often preheated, although manganese ores are generally unsuitable for preheating.

Feed chutes connect the bottom of the feed bins to the furnace. The lower sections of the feed chutes, where they protrude below the furnace roof, may be water cooled or thermally insulated. They are usually fitted with wear liners to accommodate the abrasive feed material. Hydraulic chute gates are installed in the feed chutes, providing the ability to shut off the feed system to the furnace. Furnaces of this type are choke fed. This means that, under normal operating conditions, the feed chute is always open to the furnace and there is a pile of feed on top of the slag. As this material is consumed, it is replaced by material from the feed bin without the need for any control interventions. The feed piles surround the electrodes and generally extend almost to the furnace roof. The greater proportion of the feed material is fed into the center of the furnace between the electrodes.

During the furnace operation, gas and fumes at a high temperature are generated in the furnace freeboard. Gas leaves the furnace through exhaust gas ports in the furnace roof. In closed (hermetic or gas-tight) furnaces the CO gas is not combusted prior to leaving the furnace. After quenching and scrubbing, the furnace off-gas may be combusted in the preheater, where the heat is used to preheat the feed material. Carbon monoxide (CO) gas, which is a product of the reduction process, is explosive in air at concentrations between 12% and 75%. Hydrogen gas may be formed if there is high moisture content in the feed or if there are water leaks. It is explosive in air at concentrations between 4% and 75%.

Furnace pressure is usually controlled to slightly below atmospheric pressure by means of a damper in the exhaust gas ducting to ensure that exhaust gas does not escape from the furnace through any apertures. The gas ducting is optimized to prevent the settling of dust in the duct. Inspection hatches are provided where possible to allow for inspection and cleaning of the inside of the ducting. However, these are only accessible when the furnace is off due to the dangers inherent in the CO gas.

The ducting close to the furnace, where the gas is hottest, may be water cooled or it may be refractory lined to protect the structure from the hot gas. The exhaust gas ducting is usually provided with expansion joints to accommodate thermal expansion. From the furnace, the gas is ducted to a gas cleaning plant, where it is cooled and particulate material is removed. In addition to dust, volatile tars released by the reductants must be removed by the gas cleaning system. In furnaces with closed roofs, wet scrubbing systems are usually used.

In a wet scrubbing system, the gas is quenched to saturation temperature and particles are removed as the gas is mixed with water. A wet venturi scrubber usually has two venturi sections. In the first venturi section, the gas is quenched and coarse particles are removed. Approximately 80% of the dust particles are removed from the furnace off-gas in the first gas cleaning stage. In the second, high-energy venturi, fine particles are removed. Entrained water droplets are separated from the gas by means of a cyclone situated after the second stage venturi. Clean water is used for gas cleaning. The dust-laden water leaving the scrubber flows to a collector sump from where the slurry is pumped to a slurry water treatment plant.

The furnace exhaust gas is drawn from the furnace and through the gas cleaning system by an induced draft fan train. A motorized damper upstream of the gas cleaning plant controls the furnace pressure. The pressure in the exhaust gas system is controlled by means of the damper and a variable speed drive on the fan to maintain both the required furnace pressure and the required pressure drop across the gas cleaning system. A recirculation line from the outlet of the scrubber may be included in the upstream ducting to control the gas temperature and flow rate to ensure safe and optimal operation of the scrubber. Gas leaving the scrubber is sufficiently clean to meet stringent environmental emissions requirements. From the scrubber, gas is returned to the preheater if one is employed, or it enters the stack, where it is flared. If an energy recovery system such as a waste heat boiler is employed in the downstream process, the gas is sufficiently clean at this point to enter the system. Upstream from the gas cleaning plant a bypass line leads to an emergency stack where the raw gas may be flared when the gas cleaning plant is not operational.

In open and semiclosed furnaces, dilution air is drawn into the furnace roof to facilitate combustion of the CO gas and the reduction of the exhaust gas temperature. After this combusted gas leaves the furnace, it is cooled in a radiant heat cooler (also known as a trombone, serpentine or hairpin cooler), prior to entering a bag filter plant where the dust is removed.

A trombone cooler consists of a series of vertical pipes and bends creating a radiant heat transfer area through which the gas temperature can be reduced to a level below that required for auto ignition (630°C for CO) and suitable for safe operation of the bag filter plant. There is usually a bypass duct across the cooler, fitted with a normally closed damper, which may be used to isolate the cooler for maintenance.

The operation of a ferroalloy furnace may be considered semicontinuous. The furnace is choke fed with raw feed material, and operates at an essentially constant power. Tapping of metal and slag is performed periodically.

Metal and slag are usually tapped from a single tap hole. Tap hole blocks are manufactured from carbon and graphite and extend from the hot face of the lining through the shell. The sidewall lining is thickened locally around the tap hole block. The furnace tap hole may be drilled open, with the final breakthrough accomplished using an oxygen lance. The drill is mounted on a pivot pedestal adjacent to the furnace. The tap hole is closed by means of a clay gun mounted on the same pedestal. There may be a fume extraction system located above the tap hole to capture some of the fumes released during the tapping process. The extraction system is connected to a dedicated gas cleaning plant to clean the fumes prior to exhausting into the atmosphere. A ferrochrome furnace and its tapping bay are shown in Figure 4.7. The tap hole is in the center of the photograph, with the clay gun and drilling machine visible on the left. The fume extraction hood is mounted above the tap hole.

During tapping, slag and metal may be separated by means of a skimmer. Metal leaving the furnace travels along a launder section where the metal

FIGURE 4.7 A ferrochrome furnace viewed from the tapping bay. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

passes below the skimmer block and into a ladle from where it is removed to a casting bay. In the casting bay, metal may be cast into iron molds or it may cascade into casting beds made of river sand, fine feed material, or slag. The metal solidifies to form ingots, which are removed by means of an overhead crane once they have cooled sufficiently. Ferrochrome and ferrosilicon may be granulated in water as an alternative to casting.

Slag is diverted from the skimmer block via a side launder. The slag may be collected into a ladle or it may flow along a slag launder to a slag pit, where it is water cooled. The cooled slag is removed from the slag pit to the metal recovery plant or the slag dump by heavy vehicles. Molten slag can be transported to the slag dump in ladles on custom-made slag pot carriers.

4.1.3 Silicon Metal Furnaces

Silicon metal is usually smelted in circular AC furnaces, with typical capacities of 25 MVA and diameters of 10 m. Although they are generally similar to ferrosilicon furnaces, they embody some unique design features to accommodate the requirements of the process.

The furnace shell is a reinforced steel structure with the base and sidewalls welded together. The base of the shell is usually dished to follow the curve of the refractory lining of the hearth. This configuration provides a constant hearth thickness resulting in a uniform hearth temperature and even heat transfer from the hearth. The shell is mounted on a rotating table, allowing the entire crucible to rotate through 360 degrees, at a speed of between 1 to 8 degrees per hour. The table is mounted on a set of wheels, and is driven by a geared motor assembly. The rotating shell permits access for the rabbling cars to the entire circumference of the shell over a period of some days. Stoking or rabbling is performed periodically in order to break the crust and to agitate the raw material to promote even processing of feed and gas formation. As the electrodes are fixed to the building structure and do not rotate with the shell, the rotation of the shell allows the electrodes to evenly burn away silicon carbide formed in the reduction process in the colder regions further from the reaction zone which has accumulated on the sidewalls, thus maintaining a consistent crucible size and shape. The shell, rotating mechanism, and tap hole fume extraction ducting of a silicon metal furnace are shown in Figure 4.8.

The sidewalls of silicon metal furnaces are usually uncooled, with heat transfer occurring purely by natural convection. The reinforcing ribs and stiffeners act as cooling fins, thus assisting in the cooling of the shell. Forced air-cooling may be applied to the base, although this is not as common as in other ferroalloy furnaces.

The furnace lining is based on an inner crucible made of high quality carbon material, in a similar manner to ferrosilicon and other ferroalloy furnaces. High-quality alumina bricks are used between the crucible and the shell and in the freeboard region. As these furnaces have no forced cooling on the shell, the lining design is optimized to remove the required heat from the crucible while maintaining a safe shell temperature. The shell usually has an angled top section, which facilitates the flow of air across the shell and into the furnace roof (smoke hood).

Multiple tap holes are set into the sidewall at regular intervals. Tap holes are usually made of carbon blocks protruding through the shell. Silicon metal tapping may be a continuous operation or a batch operation with tapping taking place approximately every 2 hours. Silicon metal is tapped into refractory lined ladles, which are preheated by means of gas burners. Ladles are mounted on ladle carriages, which are transported to the casting bays by small tractors.

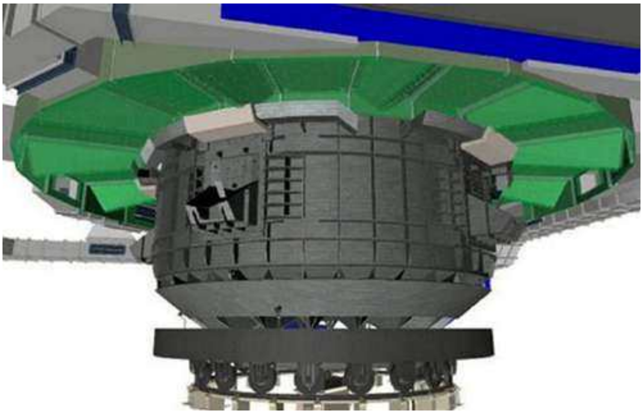

FIGURE 4.8 Shell, rotating mechanism, and tap hole fume extraction ducting of a silicon metal furnace. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

The furnace tap hole may be opened using a stinger, which is connected to a bus bar system from the furnace transformers, or by means of a hydraulic drill. Many producers favor the drill, as it creates a more accurate and consistent hole, whereas the stinger tends to create a large hole after repeated operations. The equipment is suspended from an overhead rail, where the floor is required to provide 270-degree access around the furnace for the tapping operator. An alternative to the permanent floor is the use of a mobile platform, which can be moved 360 degrees around the furnace to provide tapping access to the tap hole in use. This platform moves on a set of rails adjacent to the ladle car rails. The tap hole is closed by means of a clay gun.

A tapping fume extraction hood may be installed on the underside of the operating floor around the full circumference of the furnace, to be able to extract fumes from any position where the tap-holes may be located. A removable plate with a castable refractory may be provided above the tap hole to deflect the flames, hot gas, and fumes generated during tapping into the tapping fume extraction hood. The hood is divided into compartments. During the tapping process, only the compartment above the working tap hole is opened. This ensures that the fumes generated during the tapping process are effectively extracted to the furnace bag filter plant or into a separate dedicated bag filter plant. The fume extraction duct includes a hood, which extracts fumes from the ladle refining station.

Silicon metal furnaces are generally of a semiclosed construction. The furnace roof and smoke hood do not rotate with the furnace shell but are fixed to the building. The annular gap between the top of the furnace shell and the smoke hood allows for ingress of dilution air. As this air mixes with the CO, SiO_2 and SiO produced by the smelting process, the gas is oxidized and leaves the furnace as CO_2. The furnace off-gas contains SiO_2 (silica) dust, also known as condensed silica fume, which is a saleable byproduct of the process.

The furnace roof generally consists of horizontal water-cooled steel panels suspended from the building structure and vertical smoke hood doors and panels. These form a structure which makes allowance for ports through which the electrodes pass, one or more off-gas ports, and multiple feed ports through which the feed chutes protrude into the furnace. Panels in the central area between the electrodes are manufactured from a nonmagnetic stainless steel to avoid electromagnetic heating, and are insulated from each other to prevent stray currents circulating in the roof. Roof and side skirt panels may employ a plate and baffle construction, or they may be fabricated entirely from thick walled steel pipes. The inside of the smoke hood and roof, including the side skirts and lifting doors, is lined with a high temperature refractory castable to protect the steel from the high temperatures generated by the combustion of the CO gas. The smoke hood is fitted with water-cooled doors, which may be raised and lowered hydraulically to provide access for the stoking car and for maintenance. The furnace roof and smoke hood of a silicon metal furnace is shown in Figure 4.9. This design has two exhaust gas ducts.

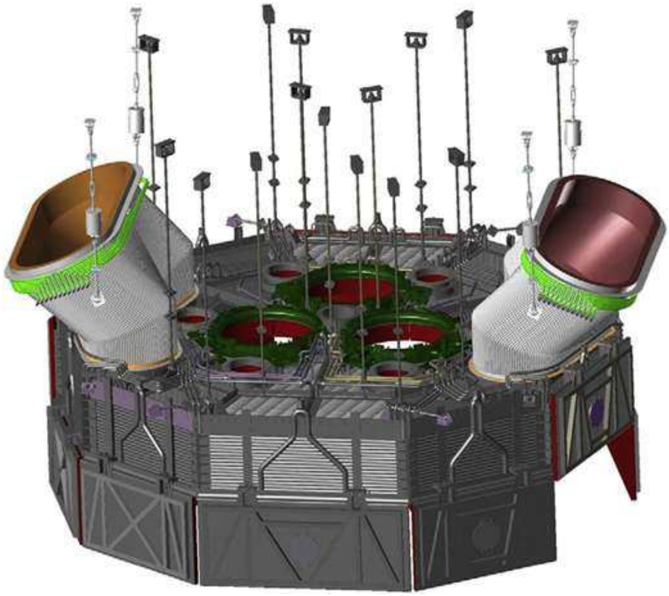

FIGURE 4.9 Smoke hood of a silicon metal furnace. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

On leaving the furnace, the gas is cooled in a radiant heat cooler prior to entering a bag filter plant where the dust is removed from the gas. In the bag filter plant, the dust-laden air passes through a number of filter bags in which dust particles are captured. The solid particulate matter remains on the filter cloth while cleaned air is passed into the connecting ductwork to the main induced draft (ID) fan which discharges into the clean gas stack. The filter bags are cleaned regularly. The dust dislodged from the filter bags is collected in the bag filter hoppers and removed to a storage silo. The temperature of the gas entering the bag filter plant is controlled by allowing some recirculation of colder downstream gas. Provision is made for bypassing the bag filter plant by sending gas to the emergency stack. The hot gas may be used in a waste heat boiler or other energy recovery system in preference to the radiant heat cooler.

4.1.4 Ferronickel Furnaces

Ferronickel is smelted from calcined nickel oxide in circular or rectangular AC furnaces. Furnaces are typically large, with power ratings of up to 120 MVA (75 MW). Rectangular furnace configurations are generally used for the larger furnaces. Ferronickel furnaces may be operated in a shielded-arc mode or as slag resistance furnaces. The typical hearth power densities of the order of 200 kW/m^2 combined with the degree of superheat of the slag normally necessitate the use of cooling elements made of copper on the sidewalls.

In a rectangular or six-in-line furnace, six electrodes are arranged in a line along the center of the furnace. The electrodes are connected in pairs, two adjacent electrodes being fed from the positive and negative connection of the same phase. The metal tap holes are located on one end wall, at a lower elevation to the slag tap holes, which are located at the opposite end of the furnace. In a rectangular furnace, the shell does not provide the same structural support to the lining as in a circular furnace. Rectangular furnaces are therefore held together by a system of steel tension rods and springs. A schematic view of a section through a six-in-line furnace is shown in Figure 4.10, and a cross-section of the smelting plant is shown in Figure 4.11.

The base plate of a ferronickel furnace is usually flat, with a dished hearth. In a circular furnace the dished hearth is saucer-shaped, whereas in a rectangular furnace the hearth is dished only across the short axis of the furnace. The slag produced by the process is chemically aggressive to refractory lining materials, necessitating particular attention being paid to the choice of lining materials and generally resulting in shorter lining life than in other ferroalloy smelting processes. Carbon linings are not used. The brick in contact with metal and slag is usually a low porosity magnesia chrome refractory brick.

The base plate is cooled by forced air ventilation, whereas the sidewalls are fitted with copper cooling elements with integral water passages, which are set into the refractory lining. These provide the capacity to remove heat fluxes >200 kW/m^2 through the sidewalls and are a feature of linings employing a "freeze lining" (autogenous lining) design, where a layer of frozen slag protects the sidewall refractory from attack by the molten slag. The sidewall at the interface between the metal and slag is particularly vulnerable to damage as it is alternately exposed to metal and slag. Erosion or corrosion of the lining is limited by cooling the refractory sufficiently that a stable layer of frozen slag forms on the hot face of the cooler. The slag is

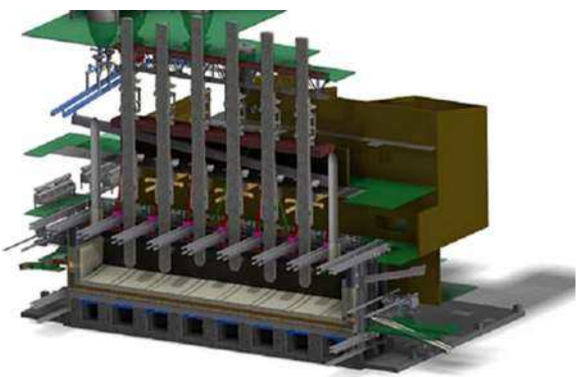

FIGURE 4.10 Schematic view of a six-in-line furnace crucible. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

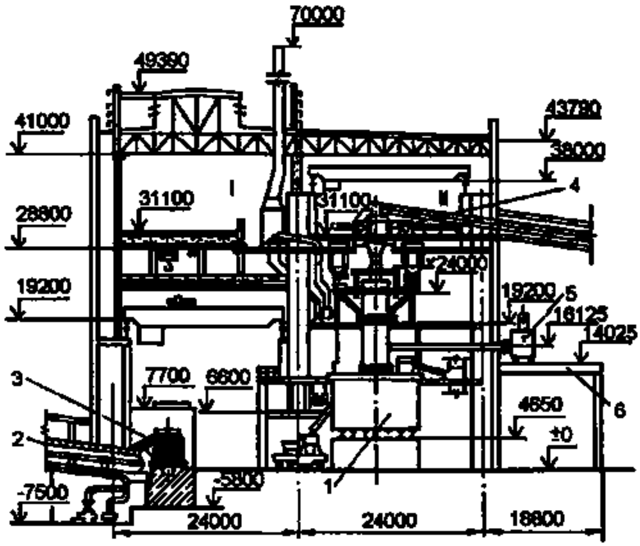

FIGURE 4.11 Schematic of a typical smelting plant with high-power rectangular furnaces of 63 MVA. I, tapping yard; II, furnace section; 1, furnace; 2, casting machine; 3, ladle; 4, conveyer charge feeder; 5, electric transformer; 6, power section support. Dimensions in mm. *(By permission of Gladkih et al., 2007.)*

chemically inert when frozen, and therefore acts as a refractory barrier between the furnace contents and the lining.

Copper coolers have been produced in a variety of geometric configurations. They may be broadly classified into two types: shallow cooled, where the copper element is inside the furnace but the water passages are located on the outside of the furnace, and deep cooled, where both the copper element and the water passages are inside the furnace. The cooling water circuit is a closed system containing treated water. Water is cooled in a heat exchanger or cooling tower. There is often an emergency cooling water system, which is activated in the event of failure of the pumps or other components of the cooling system in order to prevent excessive temperatures on the furnace.

The furnace roof is constructed of brick or refractory castable or a combination of brick and castable. Rectangular furnaces may be fitted with arched roofs, where the arch terminates in a skewback mounted on the top of the sidewall. The arch is compressed using an arrangement of buckstays and springs. Circular furnaces may be fitted with domed roofs, but these are generally only suitable for small furnaces. Suspended bricks are common, where each brick is suspended from a hanger attached to a steel roof structure. Apertures for the electrodes, feed ports, sounding ports, and exhaust gas ducts are provided in the roof refractory. The furnace roof may be made gas tight if the process produces a significant amount of CO, although this is not always necessary.

Metal is tapped periodically from the metal tap holes into a refractory lined launder, which discharges into a ladle. The tap hole blocks are water-cooled copper elements into which the refractory of the tapping channel is set. This configuration extends the campaign life of the tapping channel. The metal tap holes are opened and closed by means of a tap hole drill and clay gun, mounted on rails above the tap holes.

Slag tap holes are 700 to 1000 mm above the metal tap holes, and they are situated across the furnace from the metal tap holes. The slag tap holes are opened and closed by means of a tap hole drill and clay gun, mounted on rails above the tap holes. Slag is tapped periodically into launders, from where it may be transferred into ladles, dumped into slag pits, or granulated using a high volume of pressurized water. The slag launders may be refractory lined, or they may be water cooled.

Raw material in the form of hot calcine is received from the rotary kilns in calcine containers mounted on transfer cars, which run on rails between the kilns and the furnace. The containers are lined with thermally insulating castable to retain the temperature of the calcine and to protect the steel structure of the containers. The calcine bins are lifted using an overhead crane and discharged into feed bins, which are similarly lined with thermal insulation. The system is provided with multiple containers, cars, and cranes so that any feed bin may be filled at any time.

Multiple feed bins are arranged around the furnace to provide optimal positioning of the feed chutes. Feed material discharges into the furnace in batches through the feed chutes via gas-tight valves. The batching method may range from completely manual to fully automatic. The height of the feed piles in the furnace is monitored and used to control the batching process.

In open furnaces, dilution air is introduced into the freeboard of the furnace crucible to combust the CO gas generated by the reduction process and to reduce the gas temperature. Exhaust gas leaves the furnace in a water-cooled steel duct. Further downstream, where the gas is cooler, a refractory lined duct may be used. In a similar manner to other ferroalloy smelting processes, exhaust gas passes through a radiant heat cooler prior to entering the bag filter plant. An induced draft fan draws exhaust gas through the ducting. After the bag filter plant, the system vents to a stack. An emergency stack is provided through which gas may be vented into the atmosphere should the gas cleaning plant not be available. Ferronickel furnaces may also be hermetic, where the gas leaving the furnace is cooled in a wet scrubber prior to flaring in the exhaust stack.

Tapping fume from the slag and metal tap holes is extracted from above the tap holes and launders and introduced into the exhaust gas duct, where it cools the gas and provides additional dilution air.

4.1.5 DC Furnaces

The use of DC arc furnaces for the smelting of ferrochrome has increased. Whilst the operating temperatures are the same for AC and DC furnaces, the raw material feed requirements differ. AC furnaces are choke fed and require lumpy feed material in order to provide a sufficiently porous bed to facilitate the upward percolation of the generated gas through the feed material. Too great a proportion of fine material in an AC furnace will reduce the porosity of the bed and result in pressure excursions and unstable operation. DC furnaces operate with an open slag bath and can therefore accommodate fine feed material which falls directly into the slag bath. A further consequence of the open bath operation is that lower grade, and consequently cheaper, reductants may be used. DC furnaces can operate at higher power densities than AC furnaces. A DC furnace is therefore usually smaller than the corresponding AC furnace of the same power rating. DC furnaces provide capital cost savings compared to AC furnaces where there is a large proportion of fine feed material, as these materials may be fed directly into the furnace, thus obviating the need for briquetting or other agglomerating equipment. This cost saving is offset against the higher cost of a transformer rectifier over an AC transformer and the more expensive graphite electrode technology, which is usually used.

The DC furnace operates with an open arc, which may be 700 mm long, unlike the submerged arc found in an AC furnace. Fine feed material is fed around the circumference of the electrode. A certain proportion may be fed through the center of the electrode. The feed material is deposited on top of the molten slag, but there may not always be sufficient to cover the slag bath. Conditions on the surface of the slag are generally quite turbulent, with slag splashes forming accretions on the roof and upper sidewalls. The roof and upper sidewalls may be exposed to direct radiation from the arc and the surface of the slag bath, representing a substantial heat load on these components. The sidewalls are cooled using serpentine cooling channels welded to the outside of the shell. This cooling may be supplemented by copper plate coolers (embedded into the refractory lining) to ensure that a layer of frozen slag is maintained on the sidewalls. The base of the furnace is cooled by forced air convection. The shell of a DC arc furnace is shown in Figure 4.12. The cooling water channels on the sidewall are visible. The rectangular holes in the upper shell allow the copper coolers to pass through the shell.

FIGURE 4.12 The shell of a DC furnace. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

A DC furnace requires at least two electrical connections: a cathode and an anode. The conventional current (electron flux) passes from the cathode to the anode. Most of the actual current is carried by electrons moving from the graphite electrode tip (cathode) to the slag bath (anode) under the influence of the electric field between the electrode tip and the slag bath. The result is that in a DC furnace, an electrode operated as a cathode shows much less wear than an electrode operated as an anode.

A single prebaked graphite electrode similar to those used in AC furnaces forms the cathode. The anode is embedded into the lining of the hearth, which usually has a concave dished shape. The two most common anode configurations are a conductive hearth and a pin anode. A conductive hearth is formed by using carbon or carbon-coated bricks and enhancing the electrical conductivity of the hearth bricks by the inclusion of thin steel plates between bricks. The anode pin configuration utilizes four copper anodes protruding some distance into the hearth. The anodes are connected by means of a copper plate near the base of the hearth.

The DC furnace generally has a gas-tight roof in the same way as the AC furnace, and the raw material handling, off-gas handling, and tapping equipment is the same for both furnace types. A DC furnace is shown in Figure 4.13. The single graphite electrode with its clamping mechanism and the gas-tight, water-cooled roof are visible in the center of the picture.

FIGURE 4.13 General view of a DC furnace. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

DC furnaces are not used for the smelting of ferromanganese and silicomanganese because the high vapor pressure of manganese results in unacceptable metal losses in the gas phase.

4.1.6 Electrical Supply and Operation

Furnaces receive power from the electrical substation by means of a high voltage supply, in the kilovolt range appropriate to the furnace MVA rating. The voltage is reduced to that required by the AC furnace by means of a single, three-phase, step-down transformer or three single-phase, step-down transformers. Power from the substation is supplied to a DC furnace by means of a transformer-rectifier.

The low tension current is carried from the transformers to the electrodes by air-cooled bus bars or water-cooled copper bus tubes. Flexible conductors are fitted between the ends of the bus bars and the transformer flag connections to avoid placing mechanical loading on the transformer connection flags. Cooling water is piped to the bus tube ends by nonconductive flexible piping in order to insulate the piping system from the bus tubes. The bus bars terminate at fixed positions around each electrode. Flexible water-cooled copper conductors are used to carry both current and cooling water from these terminations to the terminals for the contact shoe riser tubes on the electrodes. These flexible conductors are shown in Figure 4.14.

The electrical insulation of conductors from each other and the furnace structure, as well as the insulation of the furnace from the building structure, is an important detail of furnace design. The large magnetic fields generated by

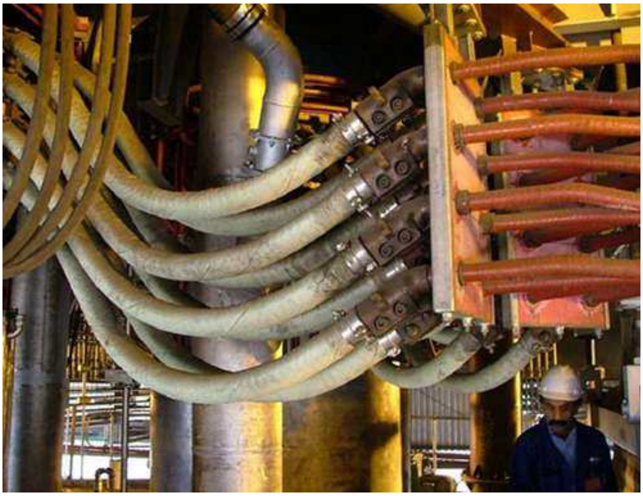

FIGURE 4.14 Flexible water-cooled copper conductors at the electrodes. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

the electrode current give rise to induced currents in magnetic materials in their close proximity. It is good practice to use nonmagnetic materials, such as stainless steels, for the furnace steelwork close to the electrodes.

4.1.6.1 AC Furnaces

The incoming voltage is reduced to that required by the AC furnace by means of a single three-phase, step-down transformer or three single-phase, step-down transformers. Voltage changes on the secondary side of the transformers are made using on-load tap changers.

The supply to the primary side of the transformers may allow star/delta switching to increase the secondary voltage range, thereby increasing the flexibility of the transformer. The star configuration is used when low electrode currents are used—for example, during startup or electrode baking schedules. The star/delta switching equipment is located in the furnace building for convenient access. Switching between star and delta is performed at the star/delta switch location, and it is never done remotely from the control room. The transformer secondary windings are connected to the three furnace electrodes in the delta configuration with the delta closed at the contact shoes on the electrodes.

AC furnaces may be circular or rectangular. Most AC furnaces are powered from a three-phase electrical supply. The most common furnace type for ferrochrome, ferromanganese, ferrosilicon, and silicon metal is a circular AC furnace with three electrodes arranged in a triangular configuration.

Rectangular or six-in-line furnaces are used in the smelting of ferronickel, high-carbon ferromanganese, and silicomanganese. In these furnaces, the electrodes are arranged in a line along the center of the furnace. The electrodes are connected in pairs, two adjacent electrodes being fed from the positive and negative connection of the same phase. Although three-electrode circular furnaces and six-in-line rectangular furnaces are the most common, a number of variations of these furnace configurations have been built. These include three-in-line rectangular furnaces, which are electrically identical to the circular three-phase furnace, and single-phase furnaces with two electrodes or one electrode and a bottom connection.

The current in an AC furnace passes through an electrode, through the arc, and into the conductive material in the bath, predominantly the molten metal, from where it passes into the other electrodes to close the circuit. Different arc configurations and operating modes are possible, based on the electrical properties of the feed material and slag.

The uncorrected power factor $\cos(\varphi)$ of most submerged arc ferroalloy furnaces lies in the range of 0.75 to 0.85, which is fairly low. For economic reasons, the power factor can be improved to approximately 0.95 by the installation of power factor correction capacitors.

With their short arcs and resistance heating component, submerged arc furnaces cause much less flicker and harmonic distortion than the much more common scrap melting furnaces in the steel industry. Due to the conductivity of steel, scrap-melting furnaces are forced to generate their heat almost entirely from long arc operation, which necessitates extensive measures to reduce flicker and harmonic distortion on the electrical supply system.

4.1.6.2 DC Furnaces

DC furnaces are increasing in popularity for some processes. A single carbon electrode similar to those used in AC furnaces forms the cathode. Due to the high current density, the cathode is usually a prebaked graphite electrode. Søderberg (self-baked) electrodes are not used. The anode is embedded into the lining of the hearth. A DC furnace usually has a relatively long open arc, operating in a similar manner to a steelmaking electrical arc furnace.

A DC arc furnace is powered by a single transformer connected to the utility which powers the 33 MV bus, in turn transferring power to the furnace power supply and auxiliary loads. A vacuum circuit breaker is used to feed power to two rectifiers through a furnace transformer. The rectifiers produce the resulting DC voltage. Reactors ensure low ripple content in the DC current, providing arc stability and reducing harmonic levels.

The negative DC voltage output from the rectifiers is transferred to the electrode column by means of water-cooled copper bus tubes and flexibles. The copper flexibles are connected to copper contact shoes, which transfer the DC voltage to the graphite electrode. Contact between the copper contact shoes and the graphite electrode is maintained by means of a pressure clamping system. The positive DC voltage output is transferred to the copper anode dish by means of water-cooled copper flexibles.

Due to the positioning of the single power supply and asymmetrical bus tubes, high asymmetric magnetic fields are present inside the DC furnace, particularly in the arc zone. This causes skewing of the electrical arc, resulting in uneven refractory wear. This may result in premature failure of the furnace refractory lining. For this reason, magnetic compensation is provided to correct the arc skewing.

4.1.6.3 Electrodes

The electrode column provides the path through which electrical power is transferred from the switchgear to the material in the furnace. Current passes into the furnace from the transformers through bus bars or water-cooled bus tubes into a number of copper contact shoes placed around the circumference of the electrode. The contact shoes are clamped onto the electrode by means of a pressure ring designed to force the contact shoes against the electrode in order to provide good electrical contact for the transfer of current. The electrodes extend through the roof of the furnace and are submerged in the raw material inside the furnace (Fig. 4.15).

The electrode column includes a supporting structure for the electrode and a clamping mechanism. The clamping mechanism may be hydraulically or pneumatically powered or it may be connected to a winch. During operation,

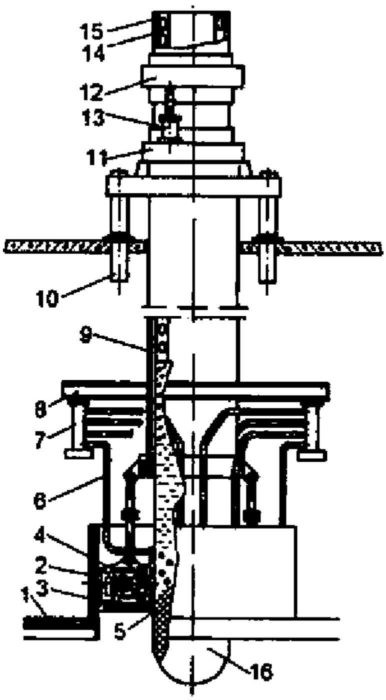

FIGURE 4.15 Schematic of the electrode (self-baked or Søderberg type) and its support. 1, furnace roof; 2, water-cooled electrode seal; 3, thermal seal; 4, pressing mechanism; 5, copper contact shoes; 6, current flexible connectors ("short net"); 7, movable shoe; 8, traverse; 9, shield; 10, hydraulic lift; 11, fixed ring of the slipping mechanism; 12, movable ring of the slipping mechanism; 13, hydraulic cylinder; 14, steel shell fins; 15, steel shell; 16, electrode. *(By permission of Gladkih et al., 2007.)*

electrodes may periodically be moved up or down by a few centimeters during operation to assist in the control of the furnace by increasing or decreasing the bath resistance, an activity termed *regulating*. This is achieved by raising or lowering the clamp assembly.

As the electrode is carbonaceous, it is consumed in the furnace. To compensate for this erosion of the electrode, it is fed into the furnace by a process called *slipping*. During this routine activity, one electrode clamp is released and the electrode, fully gripped by the other clamp, and is moved up or down by a precise amount, slipping it through the open clamp. Slipping is performed at regular intervals. The operating resistance of the furnace is determined by the furnace contents as well as the height of the electrode tip in the furnace. In a submerged arc furnace, the reaction zone tends to form near the electrode tip. With a short electrode, the reaction zone will be higher in the furnace than when the electrode is long. Likewise, moving the electrode up or down will cause short-term variations in conductivity, but these conductivity variations tend to disappear as the reaction zone reestablishes itself around the new electrode tip position. Electrode seals are provided where the electrodes enter the furnace roof. They may be active, using a compressed air powered bellows arrangement, or passive, fitted with a fiber rope seal. It is good practice to provide a heat shield around the electrodes above the furnace roof. This heat shield protects the steel building structure from radiant heat emitted by the electrode. Dust shields may be fitted over the contact shoes to prevent the accidental ingress of feed material and dust.

Three types of electrodes are used (Gasik, 1984). The optimal electrode type for any application is determined by requirements such as the required current density, the electrode diameter, and capital and maintenance costs. The electrical conductivity and diameter of an electrode determine its current carrying capacity. Electrodes used in DC furnaces can carry more current than the same electrodes used in AC furnaces, as AC current tends to concentrate on the surface of the electrode, the so-called skin effect. In AC furnaces, smaller-diameter electrodes can accommodate a higher current density than can larger-diameter electrodes. The skin effect becomes pronounced at electrode diameters greater than 1000 mm.

Søderberg (Self-Baked) Electrodes

Søderberg electrodes were invented in 1919 to overcome the size limitations of prebaked electrodes. This self-baking electrode consists of two parts, namely a steel casing and the carbon core. The casing is a relatively thin steel tube, fitted with a number of fins, which protrude part of the way into the core. The purpose of the casing is to contain the paste before it is baked and to provide a path for the flow of current into the paste. In addition, the casing has sufficient mechanical strength to withstand the force of the clamping device and the pressure ring. Once the carbon has baked, the casing is no longer required. As the temperature of the electrode increases, the casing oxidizes and all of the current is conducted through the carbon.

The core material is typically calcined (thermally treated) anthracite (~60%) or coal and coke (<40%) in a pitch or tar binder (up to 25% over carbon materials). This unbaked or green paste is fed into the electrode from the top in an unbaked form, either as briquettes of 0.5 to 1.5 kg each (Gasik, 1984) or in larger cone-shaped cylinders (up to 1 ton each). As the electrical current passes from the contact shoes into the casing and fins and paste, the resistive heating component causes the paste to soften and then bake. The green paste has a very low electrical conductivity and thermal conductivity. Green paste softens at a temperature of 50° to 80°C and spreads to fill the casing. During baking, at a temperature of 350° to 500°C, the paste undergoes a change of state accompanied by a loss of volatiles and a change of state of the pitch binder. This results in an increase in both the electrical and thermal conductivities of the material. The paste changes from electrically nonconductive to conductive as it bakes and acquires sufficient mechanical strength to support itself and to withstand the forces applied by asymmetric feed piles in the furnace and other factors. The schematic of the electrode zone structure is shown in Figure 4.16 (Gladkih et al., 2007).

The first zone (<70°C) has electrode paste being heated and sintered. In the second zone (70° to 350°C) the binder (pitch) becomes liquid; it then starts coking in the third zone (350° to 550°C). The last zone consists of baked

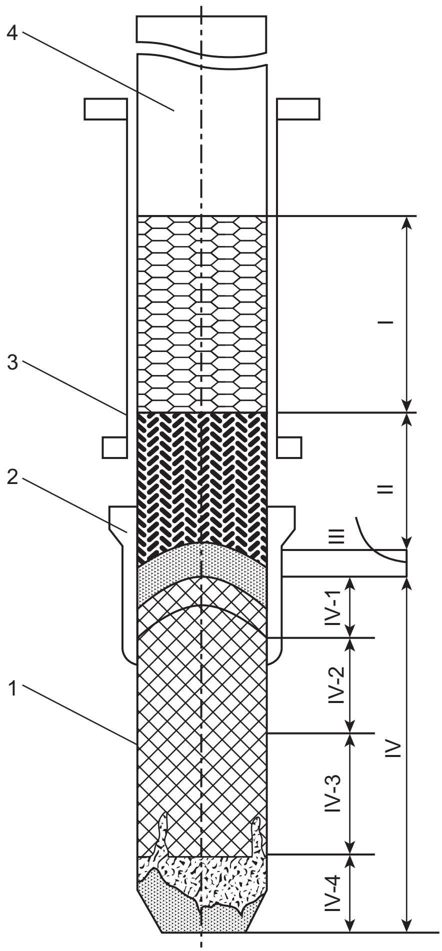

FIGURE 4.16 Zonal structure of the Søderberg electrode. I, solid paste; II, "liquid" paste; III, coking zone; IV, backed electrode (with four subzones); 1, electrode; 2, contact shoe; 3, shield; 4, electrode shell. *(By permission of Gladkih et al., 2007.)*

electrode, and in this region four subzones have been experimentally identified (Gasik, 1984), which are not based on the paste state but rather on the electrode material structural changes: the peak of the volatiles' removal at 550° to 900°C (zone IV-1), the relative stability zone at 850° to 1450°C (IV-2), the zone of carbon graphitization and ash minerals reduction at 1450° to 2500°C (IV-3), and the working tip at 2500° to 2700°C (IV-4).

The resulting baked paste forms a solid carbon electrode through which the current passes into the furnace. Typical properties of Søderberg electrode paste are listed in Table 4.4.

The carbon electrode is able to carry a high current and to withstand the high temperature generated inside the furnace. In processes such as ferrochrome and ferromanganese smelting, the electrodes carry a high current, electrode consumption is high, and baking occurs within the annulus enclosed

TABLE 4.4 Typical Properties of Søderberg Electrode Paste

Property	Value
Unbaked Paste	
Density	1600 kg/m^3
Volatile content	12–16%
Softening point	50–80°C
Melting point	100°C
Ash	<8.5%
Thermal conductivity	2.5 W/mK
Baked Paste (baked at 1000°C)	
Density	>1350 kg/m^3
Electrical resistivity (room temperature)	70 μΩm
Electrical resistivity (1000°C)	40 μΩm
Thermal conductivity	8 W/mK
Crushing strength	20 MPa
Bending strength	3–5 MPa
Maximum current density	7 A/cm^2

by the contact shoes. In ferronickel smelting, the electrodes carry a relatively low current, and the ambient temperature below the furnace roof assists baking.

As the tip of the electrode is consumed by the process, the length of the electrode is maintained by "slipping" the electrode a short distance. It is good operating practice to perform short slips, typically of the order of 20 mm, every hour, rather than performing one longer slip per shift. Long slips may be performed if required to correct a short electrode or to recover from an electrode break. These require the electrode to run under reduced current for a period of time until the paste is adequately baked. Slipping is performed by closing the fixed clamp on the electrode column and releasing the moving clamp. The moving clamp is moved upward by the required distance, and is closed against the casing. The fixed clamp is then released and the electrode is allowed to move down by the required distance. Casing segments are generally approximately 1.5 m long. As the casing moves down in to the furnace, additional segments are welded into place at the top of the electrode column. This activity is performed while the furnace is under load. Insulated barriers protect the welder from accidental contact with other electrodes or the building structure. Additional paste is loaded from above using an overhead crane.

The baking process is directly affected by the operating conditions within the furnace. As these conditions are not always the same and may not always be optimal for electrode baking, poor quality electrodes may result, which may give rise to electrode breaks. Electrode breaks are classified into two main categories, namely hard breaks, which occur in the baked electrode, and soft or green breaks, which occur where the paste is unbaked. Hard breaks may range in severity from minor, for example where a relatively short section of the tip breaks off, to major, where the whole electrode tip section, a metre or more in length, breaks off. Hard electrode breaks may be caused by a number of factors:

1. Thermal stresses or thermal shock, where the surface of the electrode is exposed to a sudden change of temperature, which creates a severe temperature gradient through the thickness of the electrode. This may lead to cracking and spalling of the electrode.
2. Underbaking, where the paste is inadequately baked and the electrical current carrying capacity of the electrode as well as its mechanical strength is inadequate.
3. Overbaking, where the paste dries out too much during baking, leading to a brittle electrode
4. Unbalanced lateral mechanical forces on the electrode due to asymmetric feed piles
5. Paste segregation, where the anthracite particles and the binder separate before baking. This leads to a mechanically weak and brittle electrode, as there is nothing holding the anthracite particles together.

Green breaks are almost always major events, as significant quantities of electrode paste are dumped into the furnace, where they may ignite and cause damage to the furnace. Green breaks are usually caused by damage to the casing.

Special operating procedures are adopted to enable recovery from all but the most minor of hard breaks. These usually involve operating the furnace at reduced load for a period while performing "long" slips, which may be up to 1000 mm, on the affected electrode in order to expedite the lengthening of the electrode. Particular care must be taken to ensure that the resulting electrode is adequately baked before full current is restored.

Søderberg electrodes may be manufactured in a wide range of diameters. As they are made of relatively simple fabricated steel members, they are not restricted to standard sizes. In addition, they are not subject to the size limitations imposed by the prebaking process, and have been manufactured in diameters up to 2000 mm or rectangular (oval) to 3000 × 750 mm. They are less expensive than graphite electrodes, as their materials of construction are not as expensive. As the electrode paste is less conductive than graphite, the current density which can be sustained by a Søderberg electrode is lower than that of a graphite electrode.

A typical electrode column for a Søderberg electrode used in a ferroalloy furnace is shown in Figure 4.17. The upper electrode column houses the clamping, slipping, and regulating arrangements, whereas the lower electrode column contains the electrical contact shoes and ancillary equipment. The electrode passes through the center of the electrode column.

The electrode column is supported on the support frame, which is attached to the furnace building structure. The hydraulic cylinders used for regulating and slipping are fixed to the support frame. There are two electrode clamps. The

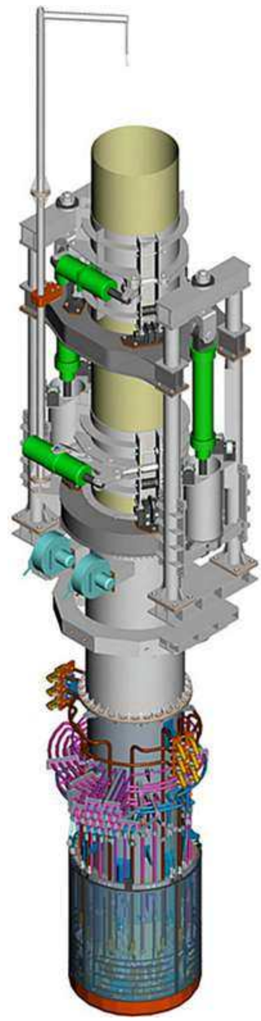

FIGURE 4.17 A Søderberg electrode column. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

upper clamp, which is normally open, is attached to the building structure. The lower clamp is normally closed and is attached to the hydraulic cylinders, allowing it to move up and down as required. The mantle is a shroud around the electrode through which warm air is forced by the mantle air fans. This air assists in heating the electrode paste. The contact shoe assembly is suspended from the mantle assembly.

The lower electrode column comprises the contact shoes, pressure ring, copper skirts, heat shields; and electrode seal. The heat shields and electrode seal are not shown in Figure 4.17.

The contact shoes are water-cooled copper segments, which transfer the electric current through the bus tubes and flexibles to the electrode. They are forced against the electrode casing by a pressure ring, a segmented arrangement of hydraulically operated bellows. The copper skirts fully enclose and protect the lower part of the contact shoes from the furnace environment. The heat shields are situated around the outside of the contact shoes and bus tubes, and protect the contact shoes, bus tube risers, and pressure ring from radiant heat from the inside of the furnace as well as protecting the live electrical components from ingress of foreign objects and dust. When the electrode is in its normal operating position, the lower part of the lower electrode column protrudes through the roof into the furnace. The electrode seal forms a gas-tight seal where the heat shields pass through the furnace roof. The entire electrode column is isolated from the furnace building structure by multiple layers of electrical insulation material.

Søderberg electrodes are more common than prebaked electrodes in ferroalloy smelters and are used in high-carbon ferrochrome, ferromanganese, silicomanganese, ferrosilicon, and ferronickel production. They are generally not used in DC furnaces, as they are unable to sustain sufficiently high current densities.

Prebaked (Graphitized) Electrodes

Prebaked electrodes are manufactured in a range of diameters, lengths, and grades. The electrodes are manufactured by pressing the green mixture of anthracite or needle coke and a binder into a mold, after which they are fired and subsequently graphitized in a furnace in a neutral or reducing atmosphere. The maximum diameter of a prebaked electrode is limited by the ability to successfully graphitize the green electrode. The controlled conditions under which they are baked result in homogeneous quality, reducing the likelihood of breaks during operation due to poor electrode baking.

Prebaked electrodes are produced in a variety of grades. Although all are made of carbon particles in a tar pitch binder, the grade of carbon used affects the final degree of graphitization of the electrode and hence its thermal and electrical conductivity, but also its cost. The thermal and electrical conductivities and diameter determine the maximum current density that the electrode can carry. Anthracite and semigraphite carbon electrodes are available in diameters from 700 mm to 1400 mm. Graphite has a considerably higher electrical conductivity, facilitating the use of a high current density in the electrode. Graphite electrodes are available in various grades and in diameters from 150 to 800 mm. Typical properties of various grades of prebaked electrodes are listed in Table 4.5.

Prebaked electrodes are supplied in sections. These sections are joined together by means of a threaded connection piece called a nipple on the end of each section. When the top of the electrode reaches a predetermined height, new sections are screwed onto the top of the electrode.

In earlier designs, graphite electrodes were supported by a hydraulically operated column and a cantilevered conductive arm. DC arc furnaces were subject to approximately 30 minutes downtime daily, as it was necessary to switch the furnace out for the purpose of joining a new section of electrode onto the existing column. Technological advances have resulted in the use of an automated electrode jointer for handling and joining the graphite electrode sections in conjunction with a central hydraulically operated electrode column for application with a DC smelting furnace, thus eliminating the furnace downtime normally associated with electrode joining. A schematic layout of such an electrode column is shown in Figure 4.18. The electrode column is supported and regulated by hydraulic cylinders. The slipping device uses springs to apply the clamping pressure and hydraulic cylinders to release the pressure to allow for slipping or back slipping. A suitable overhead traveling crane is required for lifting graphite electrode sections from ground level to the electrode floor, where jointing takes place.

TABLE 4.5 Typical Properties of Prebaked Electrodes

Grade	Diameter (mm)	Electrical Resistivity (μΩm)	Current Carrying Capacity (kA)	Maximum Current Density (A/cm^2)
Anthracite	700 1005	37	30–36 46–52	9 6.6
Semigraphite	700 1005	29	36–40 55–62	11 7.5
Graphite—high power	350	6.5	16–24	24
Graphite—ultra high power (UHP)	550 700	5	48–70 80–100	28 25
Graphite—UHP for DC furnaces	550 800	5	65–78 122–146	32 28

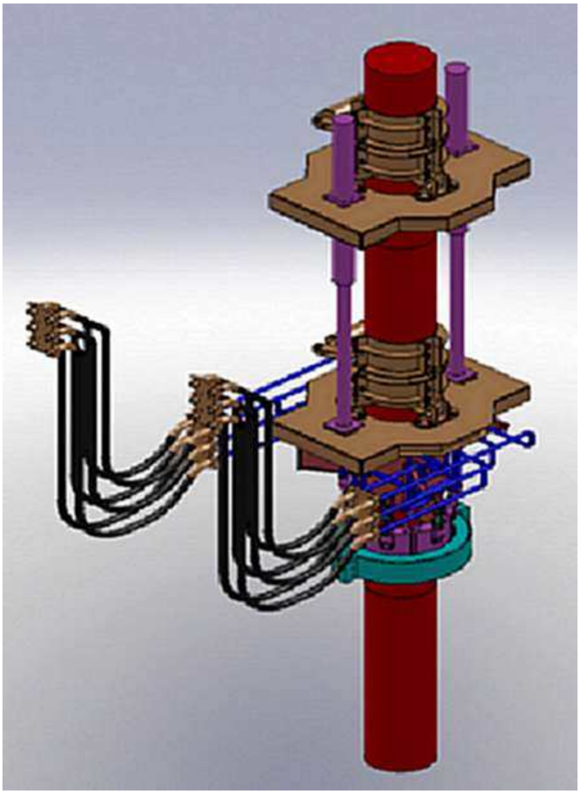

FIGURE 4.18 Electrode support column for a graphite electrode in a DC furnace. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

The high electrical conductivity of graphite electrodes renders them suitable for use in DC furnaces, and the absence of any metallic components in contact with the furnace renders all grades of prebaked electrodes suitable for use in silicon metal furnaces, although their relatively high cost is a disadvantage.

Composite Electrodes

The composite electrode was invented to fulfill a need for an iron-free self-baking electrode. These electrodes are used in low iron ferrosilicon and in silicon metal production, where the additional iron introduced by a Søderberg electrode casing is a contaminant in the product and reduces the grade of the metal.

The composite electrode has a central prebaked graphite core surrounded by a steel casing, the annulus between them being filled with Søderberg paste. The casing does not have fins. The graphite core is supported in a clamping assembly and is replenished using standard electrode sections with threaded nipples, as with conventional graphite electrodes. Current is introduced into the electrode by means of contact shoes, which are forced against the casing, as in a Søderberg electrode. The electrode paste, which fills the space between the casing and core, bakes in the contact shoe region as a result of the resistive heating in the casing and paste due to the current. The baked Søderberg paste bonds well to the graphite, but not to the steel casing. The casing is supported by an independent clamping arrangement. Slipping is performed on the graphite clamping assembly rather than the casing assembly. Both the graphite core and the baked Søderberg electrode move downward during slipping, extruding the electrode through the casing, as the casing remains at its original height. The electrode below the furnace roof therefore consists only of baked carbon. The casing clamping device provides the capacity to slip the casing with the carbon electrode should this be necessary for recovery from electrode breaks or other upset operating conditions.

The composite electrode is able to carry a higher current density than can a corresponding Søderberg electrode due to its graphite core, but is free from the maximum size limitations of the graphite electrode. The support structure and control equipment is more complex than for either a prebaked or a Søderberg electrode, however.

4.1.7 Furnace Linings

The material of construction of the lining varies from process to process and is determined by considerations such as the operating temperature of the process and the chemistry of the contents of the furnace. Refractories are sophisticated technical ceramics that are tailored to suit the demands of high temperatures, thermal cycling, mechanical stresses, and chemical attack imposed by smelting processes. Although linings are, to a certain extent, consumable items with a finite life, the choice of an appropriate lining and careful attention to installation details is an important aspect of furnace construction due to the cost of the refractory material combined with the cost of the plant downtime required to reline a furnace and the potentially catastrophic nature of a lining failure. The most common constituents of refractory bricks and monolithics are magnesia (periclase), alumina (corundum), silica and chromite, in some cases in combination (e.g., chromia-magnesia bricks). Silicon carbide and carbon are also used. The materials used in various parts of the lining are chosen for their thermal properties as well as their resistance to thermal shock, resistance to wear, their mechanical strength, or their resistance to chemical attack by the processing. Lining wear is one of the major causes of furnace failure.

Refractories, like most other engineering materials, expand on heating and contract on cooling. This effect is more pronounced in the hotter regions of the furnace, and in particular in the hearth bricks. Differential expansion between the upper and lower surfaces of the hearth may cause the bricks to bow upward, to the extent that the denser molten metal may displace them. If the furnace lining is free to expand, gaps will form between individual bricks on cooling, providing a path for metal or slag to run out of the furnace. If the lining is restrained against any movement, the force exerted on the shell by the refractory may be sufficient to damage the shell. This problem is usually overcome by accommodating a percentage of the expansion by a compressible material between the lining and the shell, usually carbon expansion paste or compressible refractory board, and by the use of expansion papers, which are inserted between bricks. As the lining is heated for the first time, the paper burns away and the bricks move into the gaps left by the paper. The balance of the expansion is constrained by the shell, which prevents the formation of gaps between bricks on cooling. A similar principle is employed in rectangular furnaces, except that the restraining force is applied to the lining by means of tension members such as tie rods and springs. A vertical force may be applied in a similar manner to reduce the formation of gaps between courses of bricks. This vertical force applied by springs has been applied to both rectangular and circular furnaces. The tensioning springs on a circular furnace are shown in Figure 4.19. The restraining force is sufficient to prevent the formation of gaps between bricks, but does not attempt to prevent thermal expansion of the lining.

4.1.8 Furnace Principal Operating Stages

The steps in the production of ferroalloys include preparation of the feed material, charging the furnace with feed, heating the feed material, reducing oxides to metal in the furnace, tapping metal, and tapping slag. This may be followed by further treatment of the metal and slag outside the furnace as well as cleaning of the exhaust gas.

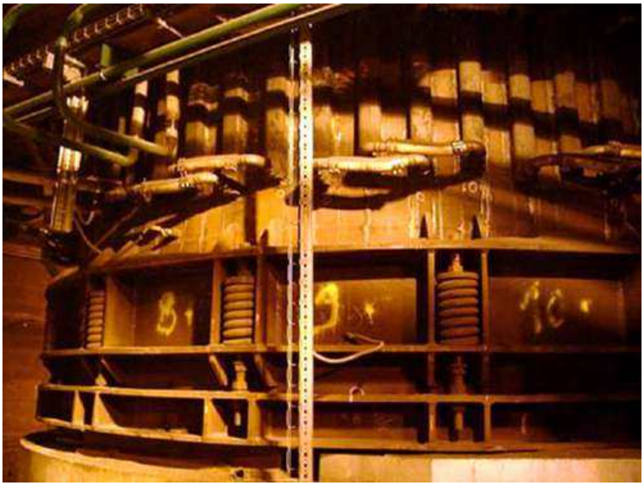

FIGURE 4.19 Tensioning springs on a furnace. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

The two extremes of furnace operation are batch mode and continuous operation. Few modern ferroalloy smelting furnaces operate in a pure batch mode where a batch of material is fed and processed, and all the metal and slag is tapped out of the furnace before more material is fed into the furnace. However, many posttapping processes, which take place in ladles or ladle furnaces, are true batch processes. In these processes, material is tapped from the furnace into the ladle furnace where it is kept warm by three electrodes whilst the conditioning process takes place. This may include blowing of oxygen and the introduction of minor alloying elements. Ladle furnaces are tapped by lifting the electrodes and tilting the entire furnace crucible once the metal conditioning phase is complete.

Most submerged arc furnaces operate in a semicontinuous mode. This is possible due to sophisticated furnace automation. The automated feed system delivers the chosen mix of feed materials into the furnace in batches based on the mass of each component at a suitable rate for the process and power setting of the furnace. In most furnaces, this means that there is a thick layer of solid feed material on top of the slag. This ensures that there is always sufficient material to efficiently absorb the heat generated by in the electrodes as well as serving to protect the furnace roof and freeboard from radiation from the slag and electrodes.

The reduction process during which the raw material is converted into product and slag takes place while the furnace temperature is within a suitable range and while there is material to process. As the raw material is processed, the metal and slag levels rise. Metal and slag are tapped from the furnace at regular intervals, usually based on the number of kilowatt-hours absorbed supported by chemical analysis where relevant. The metal and slag levels inside the furnace cannot be measured directly. The amount tapped and the duration of the tapping cycle depends on the size of the furnace and the ladles. The height of the electrodes is regulated to accommodate the rising and falling slag level.

4.1.9 Furnace Control

The quality of the product and the life of the furnace crucible are enhanced when stable conditions are maintained within the furnace. A furnace operating in a stable manner exhibits very small variations in metal and slag temperature, electrode current, electrode resistance, and electrode immersion. In addition, the electrode currents and voltages are balanced. This leads to a more consistent quality of the product, consistent electrode quality, and a reduction in the number of electrode breaks (Braun et al., 1998).

Industrial process control systems are installed to automate the operation of the furnace and ancillary equipment. The plant is fitted with appropriate instrumentation to monitor and control the equipment. This instrumentation includes flow meters, thermocouples, level sensors, pressure sensors, limit switches, and comprehensive instrumentation of the electrical operating parameters of the furnace and its auxiliaries. The output from these sensors is captured by a supervisory control and data acquisition (SCADA) system, which displays the state of each system on a computer screen in the control room and stores the data on a historian system, from where trends may be extracted. A programmable logic controller (PLC) is used to automate routine functions, such as feeding batches of raw materials, starting pumps, and shutting down systems. The PLC is also programmed to raise alarms when conditions exceed predetermined limits and to automatically initiate corrective actions such as shutting down a pump if the bearing temperature is too high or tripping the furnace electrical supply if the emergency stop button is pressed.

Many furnaces are equipped with an intelligent furnace control system in addition to the PLC. These systems contribute an additional degree of sophistication to the furnace automation, allowing automatic control of the furnace to a power (MW or MVA), current, or resistance set point as well as automating the slipping of electrodes. This is achieved by controlling the voltage on the electrodes and the resistance of the furnace circuit. The benefits of automatic furnace control include more stable furnace operation and enhanced electrode management, resulting in fewer electrode breakages and temperature fluctuations in the furnace. An example of a SCADA display summarizing furnace electrical parameters for a PLC-based furnace control module is shown in Figure 4.20.

4.1.10 Processing Hazards and Risk Management

Smelting plants, and furnaces in particular, are fraught with potential safety hazards. The presence of bulk material handling equipment, high-voltage electrical systems, extremely high temperatures, and molten metals, as well as noxious and explosive gases, exacerbates the usual risks encountered in an industrial plant. Many of the hazards can, to a greater or lesser extent, be reduced by careful furnace design. Other hazards are managed by restricting access to certain areas; the application of electrical or mechanical interlocks, alarms, and emergency stop buttons; or the use of suitable personal protective equipment.

The active management of the risks associated with smelter operation—in order to provide a plant in which the safety of employees is maximized and damage to the environment is minimized—is an important responsibility of smelter management. To this end, the production of and strict adherence to safe operating procedures, the vigilant monitoring of process parameters and equipment condition, and regular furnace maintenance are of paramount importance.

4.1.10.1 Hazardous Gases

Carbon monoxide (CO) is produced during the reduction of metal oxides. It is toxic, and inhalation of the gas can cause death. For this reason, many furnaces are gas tight and are operated below atmospheric pressure to prevent leakage of

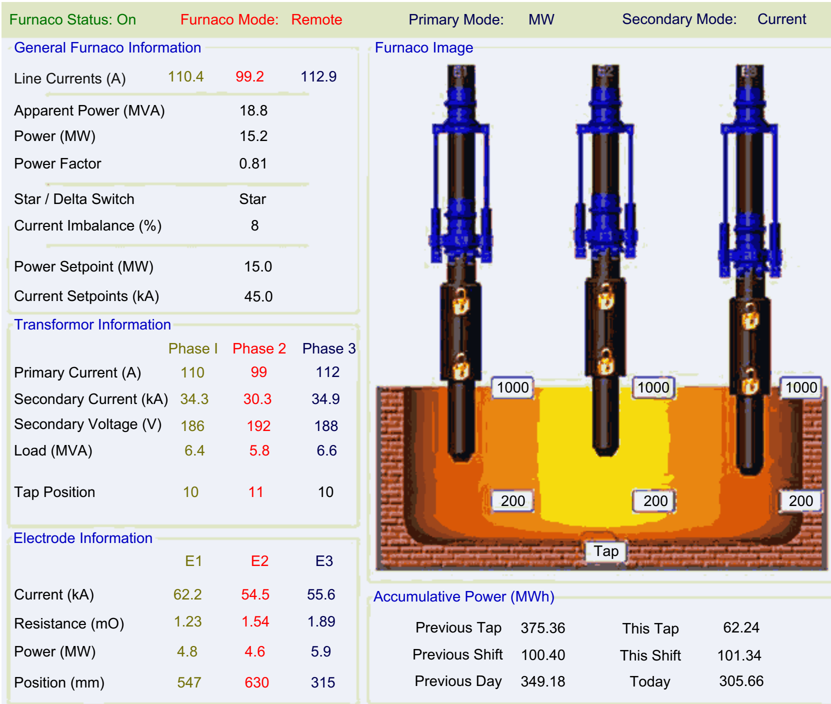

FIGURE 4.20 Typical screen for a PLC-based furnace control module. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

carbon monoxide. Access to the furnace is usually restricted while furnaces are in operation and CO monitors are often installed above the furnace roof. When it is necessary to enter an area where CO gas is likely to be present, a suitable CO monitor should be worn and accepted safety procedures for work of this nature should be followed.

In addition to its toxicity, CO gas is explosive at concentrations between 12% and 75% in air. It is flammable, with an auto-ignition temperature of 630°C. The gas-handling system is usually designed to prevent sparks, which could ignite the gas. The gas-handling system is also usually provided with rupture discs or other devices for preventing damage to the system in the event of an explosion or pressure surge.

Sulfur dioxide (SO_2) may also be produced if there is sulfur in the ore or if it is a product of the oxidation of sulfurous compounds, for example where sulfur is removed with gases in high-silicon alloys smelting via silicon sulfides. It is poisonous, but is not flammable. A respirator with suitable cartridges should be worn if this gas is present.

The volatiles contained in the pitch used as binders in Søderberg electrode paste are generally carcinogenic. Paste briquettes and cylinders should be stored in well-ventilated spaces, and excessive exposure to these fumes should be avoided.

Additionally some other compounds might present safety and health hazard in some cases. The examples of this might be chromium (VI), nickel, manganese compounds, and nonmetallic impurities (As, F, Se, etc.) when particular ores are being treated. The fugitive emissions control of the smelting furnaces is continuously being improved (Gunnewiek et al., 2010).

4.1.10.2 Molten Metal and Slag

The temperature of the molten metal and slag contained in the furnace is in the range of 1200°C to 1800°C. Consequently, any activity involving handling of slag or metal is hazardous. It is usual to prevent access to areas near, below, or above the tap holes, launders, and ladles while tapping is in progress (Els et al., 2010). Operators performing lancing and tap hole plugging operations must wear suitable personal protective equipment, and respective safe working procedures should be enforced. Figure 4.21 shows an operator performing a manual tapping operation.

Access should also be restricted in areas where ladles containing metal or slag are transported or where the hot metal or slag is being cooled. Water used for quenching of ingots may boil and produce steam.

Both metal and slag can burn through the furnace, resulting in damage to equipment. Fires may start if flammable materials are in contact with molten slag or metal. Access to the base of the furnace is usually restricted, and measures should be in place to contain any spillages in order to prevent damage to personnel or equipment. Emergency procedures, including evacuation

FIGURE 4.21 Manual tapping operation. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

procedures, provision of escape routes and the provision of firefighting equipment, should be implemented.

4.1.10.3 Water

The presence of water near the furnace presents its own potential hazards. Water leaking into the furnace from the cooling system may rapidly turn to steam on contact with molten slag or metal, resulting in an explosion. Steam explosions inside furnaces can cause significant damage to the furnace roof, electrode column, and building. Similarly, explosions may occur if slag or metal splashes into water puddles near the launders or ladles or if there are leaks in water-cooled launder sections.

Slag and metal granulation systems are particularly vulnerable to explosions caused by changes in the ratio of metal or slag to water. Design features such as emergency water systems are implemented, as well as safety interlocks, which prevent the use of the granulation system in the event of a shortage of water.

4.1.10.4 High Voltage and High Current

It is usual to restrict access to the transformers and electrical switchgear while they are energized. When it is necessary to perform maintenance of high voltage (HV) or medium voltage (MV) equipment, elaborate safety interlock systems prevent accidental contact with live electrical parts.

The electrode columns carry large electrical currents during operation. Although they are electrically insulated from the building and furnace structure, which is not at the same electrical potential, the full length of the electrode is not usually insulated. It is usual to prohibit access to the furnace roof near the electrodes while the furnace is in operation by barricading the area. Bus bars and bus tubes are usually wrapped in insulating material in areas where accidental contact is possible. Caution should always be exercised when working near a furnace, as the furnace crucible may not be earthed, and the furnace may not be at the same potential as the building. Dust, feed material spillages, or other foreign objects may cause unintended current paths or accidental earthing of live parts.

4.1.10.5 Repairs and Maintenance

As a result of the restricted access to many parts of the furnace during operation, and the potential hazards, routine furnace maintenance presents a more complex problem than on many industrial plants. Thoughtful furnace design such as the provision of redundant equipment such as a duty and a standby pump and the provision of access points for lifting gear can improve the ease of maintenance of the facility to some extent. In spite of the challenges faced by maintenance personnel, routine inspection, preventive maintenance, and the timely repair of equipment will contribute significantly to the safe and efficient operation of the furnace as well as the attainment of its desired availability.

Regular visual inspections of the plant by operating staff in the course of their normal duties are an important mechanism for maintaining a healthy furnace. In particular, the identification, investigation, and repair of faulty instrumentation will enhance the ability of the automated control systems to control the furnace in a stable manner and may be critical to the safety of personnel in the event of an emergency situation such as a furnace runout. In particular, all alarms registered by the control system should be investigated. The number of alarm signals generated by the control system should be optimized in order to alert control room staff to important issues without inundating them with nuisance warnings. In a similar manner, water leaks and other minor equipment malfunctions should be reported in a timely manner and their severity assessed to determine the optimal scheduling for maintenance activities.

Many furnaces are powered down for short periods on a regular schedule to provide opportunities for routine maintenance tasks, which cannot be performed while the furnace is live. When electrical power to the furnace is switched off, the furnace begins to cool slowly. As the furnace cools, the refractory lining cools and the electrodes cool from the outside inward. This cooling causes thermal stress in these brittle materials and causing gaps to open between individual bricks as they shrink. The duration of a furnace shutdown is therefore limited to the shortest time in which the required work may be done. A shutdown of up to 4 hours usually has no effect on the lining or electrodes, whereas longer shutdowns require more careful management. Cold shutdowns, where the furnace is drained and allowed to cool, are required if major repairs are to be performed. The furnace must be heated slowly until it reaches its operating temperature after such a shutdown.

Very little routine maintenance is required on the furnace crucible itself. Routine tapping channel replacement, particularly on metal tap holes, is performed regularly. In some furnaces, the outer tapping blocks are replaced on a weekly basis. The procedure becomes more complex when the repair goes deeper into the furnace. Replacement of the entire tapping channel usually requires a cold shutdown, which may extend to several days.

Repairs to electrode or transformer equipment require a complete shutdown and extensive electrical isolation of components. It is not necessary for the furnace to be cold, as these parts are all situated outside the furnace. However, if there is the danger of CO gas above the furnace roof, appropriate precautions must be taken to ensure that the environment is safe before maintenance staff can access the furnace roof.

Routine relining of refractory lined launders may be performed between tapping and does not necessitate powering down the furnace. Other routine maintenance tasks, such as cleaning filters and servicing pumps, can be performed while the furnace is in use.

4.2 EQUIPMENT FOR FURNACE FEED PROCESSING

The efficiency of some processes can be significantly enhanced by proper partial processing of the feed material before it enters the furnace. This may be accomplished by three broad categories of activity, namely agglomeration of fines, prereduction of ore, and preheating of raw material. One or more of these techniques may be applied to the same stream of feed material. Various techniques exist for agglomerating fine material into pellets, which are more easily processed in the furnace. A number of prereduction processes have been developed in which the reduction of the ore begins in the solid-state reaction prior to the material entering the furnace. Preheating often utilizes the calorific value of the CO in the off-gas stream to improve the energy efficiency of the furnace.

Ferromanganese and silicomanganese raw material may successfully be pretreated by sintering the ores into a sinter cake. Ferrochrome ore fines may be briquetted in a cold process, or pelletized. The feed may successfully be prereduced and fed into the furnace while it is hot. In addition, the feed, either lumpy or briquetted, may be preheated without a prereduction step. Quartzite, the raw material for silicon metal production, is unsuitable for agglomeration and preheating. However, as the silicon metal smelting process in the furnace is not as easily disrupted by fine feed material as other processes, fine material may be fed directly into the furnace.

Whether or not a particular pretreatment process will be effective in a particular context is heavily dependent on the mineralogy of the ore. It is usual to conduct extensive laboratory tests on a particular ore to determine whether it can successfully be agglomerated or whether it can effectively be prereduced.

4.2.1 Agglomeration

The raw material for the smelting of ferrochrome, ferromanganese, silicomanganese, and other ferroalloys in submerged arc furnaces is preferably lumpy (i.e., the particle size of the feed is 25 to 150 mm). In these processes, a small amount of fine material (particle size less than 6 mm) may be introduced into the furnace. However, if too much fine material is introduced, it reduces the permeability of the charge, which prevents the release of CO gas and may cause pressure excursions inside the furnace. A certain amount of fine material is generated by attrition of the lumps of ore in the raw material handling system. This excess fine material, which contains valuable minerals, cannot be processed directly and is wasted unless it can be agglomerated.

Ferrochrome fines may be agglomerated by means of a briquetting process or by the making of sintered pellets. The resulting briquettes or pellets are required to exhibit a high cold strength, so that they do not crumble during handling and do not disintegrate when dropped into an arc furnace, as well as a high hot strength, so that they do not crumble prematurely on heating. The briquetting or sintering process is not accompanied by prereduction of the ore.

Ferromanganese and silicomanganese ore fines may be agglomerated as sintered pellets in a similar manner to ferrochrome. However, it is more usual to pass the material through a sintering machine and produce a sinter cake.

4.2.1.1 Briquetting

In the briquetting plant, chromite ore fines are dried in a rotary dryer and stored in a silo. The dry ore is discharged into a mixer, where it is mixed with suitable binders. Each component enters the mixer from a bin fitted with weighing equipment in order to achieve the correct proportions in the mix. From the mixer, the material is fed into a double roll briquetting press where it is pressed into small pillow-shaped molds. Briquettes have typical dimensions of the order of 50 mm. The green briquettes are released from the molds and conveyed to a curing shed, where they are allowed to cure for a period of time, typically 24 to 48 hours. The cured briquettes are fed into the prereduction kiln, preheater, or furnace in the same way as the lumpy ore.

Various organic and inorganic binders may be employed. The most common binding material is a mixture of lime and molasses. However, various cements and resins, fuel oil, molasses, starch, dextrin, hydrated lime, bentonite, and sodium silicate have been used. The purpose of the binder is to glue the fine ore particles together in order to obtain the desired cold and hot strength. The cold strength of a briquette is a measure of its ability to resist crumbling during handling before it has cured, whereas the hot strength is a measure of the resistance to crumbling, chipping, or fracture in the raw material handling system of the furnace and, in particular, in the feed chutes and as the material drops into the furnace. As binders are consumed in the process and therefore do not add value directly to the final product, they must also be relatively inexpensive and easy to obtain. In addition, they must not introduce any undesirable trace elements into the furnace. The success of the briquetting process depends on the identification of a binder which provides optimal properties for a particular ore. Wear of the briquetting molds as a result of the abrasive nature of the ore can be a significant cost to the briquetting operation.

4.2.1.2 Production of Sintered Pellets

Chromite ore with a small amount of coke is ground wet in a ball mill, after which the resulting slurry is de-watered. It is mixed with a binder before being fed into a rotating drum or disc pelletizer, where it forms balls. Pelletizing occurs due to the rolling motion of the pelletizer without the application of pressure. The fines adhere to each other because of the moisture. The green pellets are screened to select the required size. Undersized particles are returned to the inlet of the pelletizer.

Green pellets are charged into a sintering furnace, which may be a vertical shaft furnace, although horizontal traveling grate sintering furnaces where the pellets are conveyed on a perforated steel belt are more common. After the raw pellets enter the furnace, they are heated gradually to between 300°C and 350°C, which removes the water from the pellets and allows the binding material to form chemical bonds. The heat required for this operation is obtained from hot air, which is drawn through the grate past the pellets. As the pellets progress into the furnace, the temperature is increased to the sintering temperature of 1250°C to 1350°C where the metallic ores are fused together. Heat for this stage of the process is supplied by gas burners and the coke. Waste CO gas from the submerged arc furnace or natural gas or liquefied petroleum gas may be used. As the pellets move through the downstream section of the furnace they are cooled. The sintering furnace operates as a counterflow heat exchanger. Cold air enters the sintering furnace in the cooling section, where it is drawn through the grate and past the pellets, thereby cooling them. After cooling the pellets, the gas flows into the heating section where heat is transferred to the pellets. The sinter furnace operates at a negative pressure, with airflow driven by induced draft fans. The exhaust gas is cleaned in a venturi scrubber, cyclone, or bag filter plant after leaving the furnace. Dust is returned to the sinter plant feed system. Pellets are discharged onto a conveyor that takes the sintered pellets past a series of screens to the storage bins. Undersized pellets are returned to the sinter plant feed system. Sintered pellets may be used as feed for kiln prereduction, fed into a preheater, or fed directly into the furnace.

4.2.2 Sintering of Manganese Ore

The sintering process employed for manganese ore and the siliceous ores used to produce silicomanganese results in partial reduction of MnO_2, Mn_2O_3, and Mn_3O_4 in the ore to MnO by reaction with carbon in addition to agglomerating the fine ore and coke. New technology also utilizes addition of fluxes, such as magnesia-rich components, to improve mineral composition of the sinter and increase manganese reduction efficiency (Kutsyn et al., 2012). The energy released by this exothermic reaction is utilized to drive the sintering process. The use of sinter cake as a portion of the furnace feed leads to improved furnace performance, as the bed is more stable and less prone to eruptions. Additional benefits include reduced power consumption and improved manganese recovery as well as the ability to utilize fine material, which would otherwise have gone to waste.

In the sinter plant, raw material such as ore fines, coke or coal, dust from the furnace off-gas system, and binding material are discharged from feed bins in the correct proportions through weigh feeders and conveyed to a blending system. The raw materials are blended in a rotating mixing drum. Undersized material from the sinter process is added to the mixing drum. Moisture is added by means of fine sprays to promote agglomeration of the materials. This process is known as nodulizing.

The sinter strand is an endless chain of unlinked pallet cars, which are made of a wear-resistant material. The base of a pallet is slotted to allow air to pass through the sinter bed. Sidewall plates prevent material from falling off the sides. The pallet cars are pushed along the frame of the sinter machine on wheels, driven by a series of drive sprockets mounted on the sides of the machine, which engage on the wheels of the cars. The drive mechanism is usually located at the cold end of the sinter machine. When the pallet cars reach the end of the sinter machine, they are driven around the discharge section by a second set of drive sprockets and return on the underside of the machine. A tensioning mechanism is provided to compensate for thermal expansion.

Two streams of material are fed onto the sinter strand, a hearth layer (made of sinter returns sized between 6 and 15 mm) and the sinter mix, which is placed on top of the heath layer by a roll feeder with a leveling plough. The sinter strand passes below an ignition arch where the carbon in the mix is ignited by means of fuel oil, gas, or furnace off-gas. The exothermic reaction by which the higher manganese oxides are reduced to MnO in the presence of carbon and air provides further energy to drive the sintering of the feed. The sinter burns through vertically while the bed moves horizontally toward the discharge end. Air or a mixture of hot CO-laden furnace off-gas and dilution air is drawn through the pallets by induced draft fans. The sinter cake attains a temperature of about 850°C after sintering.

After the sintering process is complete, the sinter cake is cooled. Cooling may occur on the sinter strand, or the material may be discharged off the sinter strand onto a crash deck and into a spiked roll crusher, which reduces the lumps of sinter cake to a size smaller than 150 mm, prior to discharging the lumps onto a dedicated cooling strand. In both cases, cooling is performed by forcing ambient air through the material from below. The cooling area is supplied with its own fans and wind boxes. The sinter cake cools to a temperature of less than 100°C at the end of the strand.

After on-strand cooling, when the material reaches the end of the sinter strand, the material is discharged off the pallet cars onto a crash deck, which guides the sintered material into the spiked roll crusher. As the crash-deck is subject to severe impact and abrasion, it is lined with wear-resistant material. The finger crusher reduces the lumps of sinter cake to a size smaller than 150 mm. From the spiked roll (finger) crusher the sinter cake passes over a 75-mm screen, the oversized material being crushed in a roll crusher to less than 75 mm. The material then passes on to a further screening system, where the product is separated into return fines, the hearth layer, and the sinter product. The return fines are conveyed back to the sinter feed mixing drum, while the sinter product is conveyed to the day bins for the furnace.

Dust in the waste gas from sintering is removed using an electrostatic precipitator, whereas dust from the on-strand cooling is removed in cyclones. Dust from the raw material handling system is removed in a bag filter. This dust is returned to the sinter feed mixing drum for recycling.

4.2.3 Preheating

In ferrochrome smelting in closed furnaces, the feed material may be preheated before it enters the furnace. Lumpy ore, briquettes, sintered pellets, and prereduced pellets may all be preheated successfully. The energy used to preheat the feed material comes from the combustible CO contained in the furnace exhaust gas.

A number of different preheating technologies exist, although all operate on the same principle. Rotary kilns have been used for preheating ore and pellets. However, the availability of the rotary kiln is generally lower than that of the furnace. Preheating is therefore more generally performed in a shaft kiln situated above the furnace. A single shaft kiln may be employed, or multiple shaft kiln preheaters may be used, each processing a portion of the feed material. The shaft kiln has an integral surge bin, thereby providing a buffer between raw material feed and smelting. The preheater discharges into the feed chutes and thence directly into the furnace.

A three-dimensional view of a preheating system employing three preheater shaft kilns is shown in Figure 4.22. Each kiln receives raw material feed from a feed bin, which is fitted with level indicators to continuously monitor the level of the feed material in the bin, and a position switch to stop the rotary conveyor at the specific bin when loading the feed material into the bin.

Quenched and scrubbed furnace exhaust gas passes through a booster fan (which provides the required volume flow and pressure) to the preheater

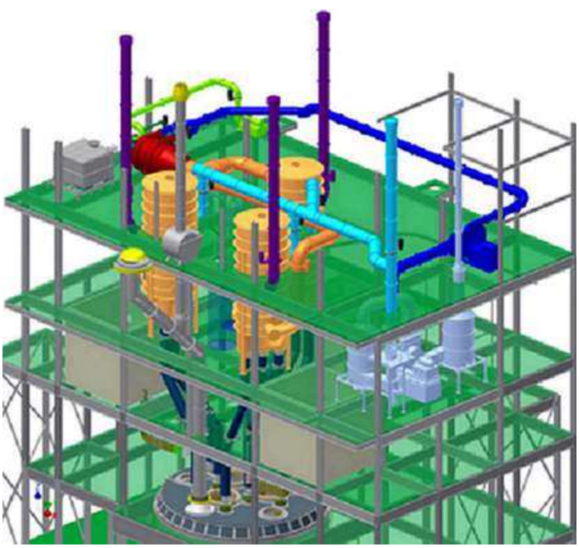

FIGURE 4.22 Ferrochrome preheating system located above the furnace. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

combustion chamber, where it is mixed with additional fresh air, supplying oxygen required to burn the gas. The CO gas is burned, after which it passes through the feed mix to heat the feed. Some of the exhaust gas from the preheater vessels is recirculated and mixed with the hot gas as it passes over the feed mix. The amount of furnace exhaust gas, fresh air, and recirculated gas is controlled in order to obtain the required temperature of the feed material. The exhaust gas from the preheater is cleaned in a venturi scrubber before being recirculated back to the combustion chamber or exhausted to the atmosphere. The temperature of the feed discharge from the preheater may be between 500°C and 700°C, although it is usually controlled in a much smaller range. The preheated raw materials are choke-fed into the furnace through a number of feed chutes. Each feed chute is fitted with a hydraulically operated rod gate, which is used to ensure that the feed chute remains full of material at all times to maintain the gas seal on the furnace.

The preheating of the furnace feed material reduces the power required for smelting inside the furnace, substantially reducing the specific power consumption of the process. In addition, any moisture contained in the feed material is removed prior to the material entering the furnace. This further reduces the specific power consumption and results in more stable furnace operation. The utilization of the calorific value contained within the CO gas further improves the overall energy balance of the process. The burning of the CO gas to heat the incoming material represents an efficient way of utilizing this energy whilst safely disposing of the noxious CO gas.

4.2.4 Prereduction

Prereduction refers to any partial reduction of the ore that is performed as a processing step prior to the feed mix entering the furnace. The sintering of manganese and silicomanganese ores is, to some extent, a prereduction process, as MnO_2 is reduced to MnO. In ferrochrome smelting, chromite ores may successfully be prereduced using a number of similar technologies, employing either a rotary kiln or a rotary hearth furnace. Up to 30% of the chromium and 90% of the iron may be reduced in this manner.

The prereduction processes used in the processing of ferrochrome start with the production of pellets. In the rotary kiln technology, sintered pellets containing ore, reductants, and fluxes enter the kiln where they are heated to 1450°C, at which temperature some of the chromite and much of the iron is reduced. Hot prereduced pellets are discharged into the furnace.

In the rotary hearth furnace prereduction technology, ore, reductants, and fluxes are milled to less than 100 μm before being blended, mixed, and fed into a pelletizing plant. The green pellets are dried using exhaust gas from the rotary hearth furnace. The pellets are sintered, reduced, and cooled in controlled zones with a maximum zone temperature of 1450°C in the rotary hearth furnace. The reduction occurs in stages in the different zones. Additional hot air is introduced into the rotary hearth furnace to control the temperature and the composition of the atmosphere in order to provide conditions conducive to the optimal reduction of chromium and iron oxides and minimization of reoxidation of the metals. Once the material has passed through the rotary hearth furnace, it is discharged onto a steel belt cooler. The cooler operates under a nitrogen-rich atmosphere, which prevents the pellets from reoxidizing and cools the pellets to approximately 600°C before they are discharged onto a second steel belt cooler, which further cools the pellets to between 100° to 150°C. The finished product is conveyed and stored in an enclosed section of the furnace raw material bunkers. These pellets may be preheated or they may be fed cold into the submerged arc furnace. Energy for the sintering and prereduction process is provided by the oxidation of the CO in the exhaust gas of the submerged arc furnace.

4.3 DOWNSTREAM PROCESSING

After the hot metal is tapped from the furnace into a ladle, it may be refined therein, after which it is cast and sized before being dispatched to the customer.

4.3.1 Refining

Ladle refining of ferroalloys is performed by injecting gas into the ladle to adjust the chemical composition of the product. This may be done from above using a lance, or it may be done from below through a porous refractory plug situated at the base of the ladle. The gas may be air or oxygen or a combination of the two gases. In silicon metal production, this process reduces the calcium and aluminum contents.

4.3.2 Casting

The traditional method of solidifying the metal is to cast it into molds where it is allowed to cool slowly. The molds may simply be a casting bed of metal fines shaped to form molds. Alternatively, cast iron molds may be used. The casting bed is arranged on an incline so that metal from the ladle passes down a runner from where it cascades into the molds. Once cast into the molds, the metal is allowed to cool. It may be allowed to cool naturally, or it may be sprayed with water to cool it more rapidly. Figure 4.23 shows the tapping of alloy into a series of molds.

A more sophisticated casting system employs cast iron molds arranged in a casting line, which moves past the ladle placed in a tilting station. The iron molds may be lined with a layer of metal fines to protect them from thermal shock induced by the rapid contact with molten metal. The layer of fines should be sufficiently thick to prevent contamination of the product by the mold and to allow easy removal of the solidified ingot. Once cast into the

FIGURE 4.23 Tapping of FeCr into molds directly from the tap hole. *(By permission of Tenova Pyromet, a division of Tenova Minerals [Pty] Ltd.)*

molds, the metal is sprayed with water to cool it more rapidly as it travels on an incline. When each mold reaches the top of the incline, the solid ingot or pig falls into a bin, breaking up as it does so. In some applications, the metal is kept in the iron mold only for the time needed for the surface to solidify sufficiently for it to hold its shape, after which it is de-molded and spray cooled. The residence time of the metal in the mold is typically 30 minutes. This practice reduces wear on the iron molds. Once the metal is sufficiently cold, it is crushed. The first stage of crushing often involves breaking the ingots into smaller sizes using a jackhammer, after which the pieces are sent to a crusher, usually a jaw crusher followed by a roll crusher. The crushed material is classified into the required sizes prior to dispatch. The crushing process is both capital and labor intensive and does not add much value. In addition, it produces fines, which have a lower market value than the larger pieces. The fines may be recycled into the furnace, used as molds, or stockpiled.

Some metals, such as silicon, ferrosilicon, ferrochrome, and ferronickel, may be granulated in water in preference to casting and crushing. During the granulation process, the hot metal is poured into a large amount of cold water, which breaks it up into droplets, which rapidly solidify. This may be achieved by pouring the metal into a jet of water at high pressure or by pouring the metal onto a water-cooled disc or a refractory brick, from where the resulting droplets fall into a tank of cold water. Control of the water to metal ratio is critical for the safe operation of the equipment and can typically be in the region of 20:1 or more. The essence of the granulation process is the rapid removal of heat from the molten metal. Loss of granulation water or any accumulation of hot metal can result in steam explosions, which may cause damage to equipment and danger to personnel. The granulation process releases steam and might also release hydrogen gas. The metal granules are dewatered and dried, after which they are classified and dispatched to the customer. They do not require further crushing. The particle size produced by granulation may be varied by adjusting the operating parameters of the granulation system, but it is also dependent on the composition of the metal and the trace elements present in the metal being granulated. Ferrosilicon and ferrochrome may produce granules in the 20- 30-mm range, whereas silicon metal can be produced in granules up to 20 mm. Atomizing is also used to produce ferrosilicon powder. Ferromanganese and silicomanganese are generally unsuitable for granulation.

Thin layer casting of silicon metal and ferrosilicon is a different approach in which the molten metal is cast by pouring a thin layer up to 100 mm thick onto a water-cooled copper plate, where it begins to solidify rapidly. One of the available technologies uses a cooled vibrating copper table for the first stage of cooling, from where the material is discharged onto two vibrating iron tables placed in series, where it begins to break up as it cools. The competing technology utilizes a cooled copper plate in the form of a rotating carousel. The material is solid within 60 seconds of casting. Once the material leaves the casting table or carousel, it is cold enough to pass to the sizing equipment. No crushing is required as it breaks up during the cooling process.

The microstructure of a metal is affected by the rate at which it is cooled. In general, the faster it is cooled, the smaller the grain size, and the more homogeneous the metal, as impurities do not have time to congregate in the areas which solidify last. A further consequence of the rapid cooling and small grain sizes is that the material particles are less brittle, with a resulting reduction in the percentage of fines produced and improved resistance to disintegration during handling in downstream processes. In addition, there are economic benefits to the elimination of the crushing operation.

Slag is tapped from the furnace in quantities equal to or greater than the metal produced and therefore presents a material-handling problem of a similar nature and size to that of the metal. The simplest method of slag disposal is to empty the ladle into a slag pit, where the slag is allowed to cool naturally. Once it is solid, it is removed by means of a crane or front-end loader and taken to a crushing plant. Slag is often processed in a metal recovery plant, where entrained metal particles are removed by jigging, after which it may be dumped on a stockpile or it may be used in refractory bricks or as an aggregate in concrete or as filling material for road construction or similar applications. Granulation of slag is a viable alternative to casting and crushing. It solidifies and breaks up the material in one step, reducing handling. Slag processed in this manner is in a suitable form for the recovery of entrapped metal.

4.4 OTHER FURNACES FOR FERROALLOYS PROCESSING

A special class of furnaces is used for production of ferroalloys using reduction by silicon. Such ferroalloys (refined ferrochrome, low-carbon ferromanganese, manganese metal, etc.) have limiting carbon (and sometimes iron) content, which restricts the use of self-baked electrodes. An example of such a furnace for smelting of metallic manganese is shown in Figure 4.24 (Gasik et al., 2009).

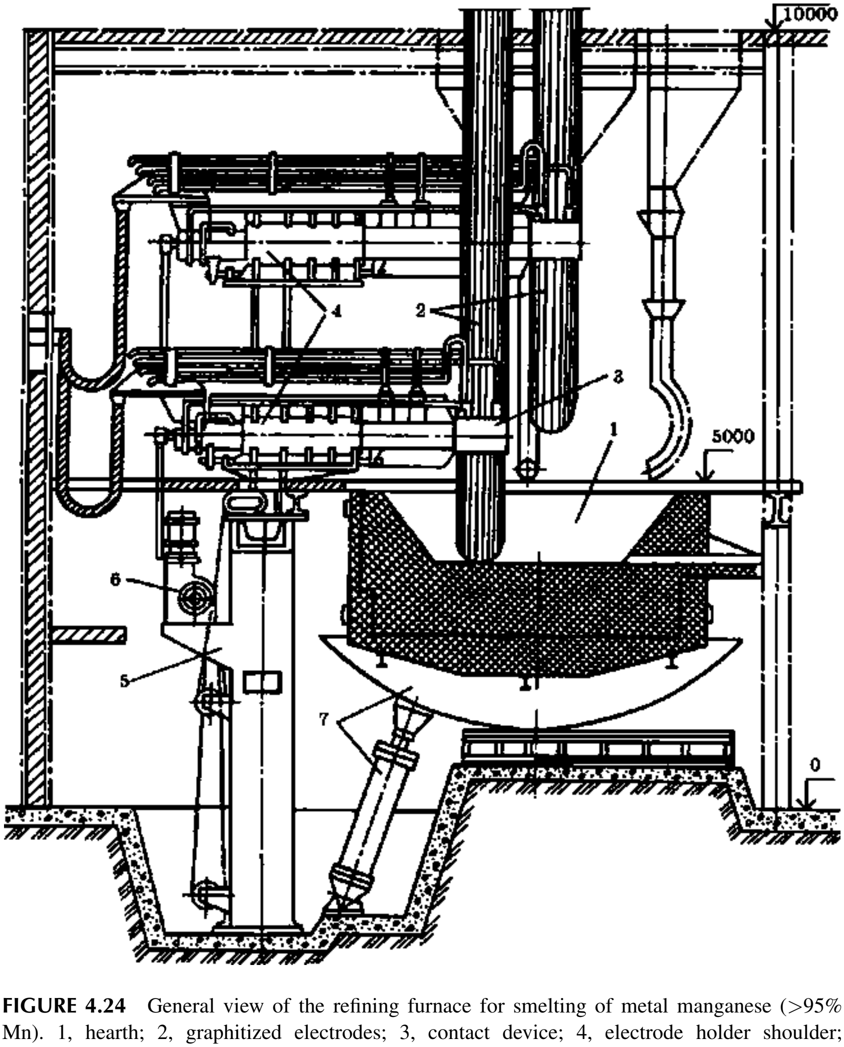

FIGURE 4.24 General view of the refining furnace for smelting of metal manganese (>95% Mn). 1, hearth; 2, graphitized electrodes; 3, contact device; 4, electrode holder shoulder; 5, telescopic support; 6, lifting mechanism; 7, tilting mechanism. Height marks are in mm. *(By permission of Gasik et al., 2009.)*

Known as *refining furnaces,* these furnaces usually operate at low power, typically less than 10MVA, and without an arc, in the resistance mode. Magnesia lining is the common feature, and the process is usually periodic. A similar type of furnace is employed for aluminum reduction processes (chromium metal, low-carbon FeCr, FeTi, FeNb, etc.), where the exothermic release of the heat of reaction of metal oxides with aluminum is not sufficient to melt the charge and the alloy, and some external heat supply is required.

Where the exothermic release of heat is sufficient, for example, in processing of ferromolybdenum by reduction with aluminum and silicon, the process might be carried without furnace. In this case the reactor is of a refractory-lined shaft type, which works periodically and is opened or disassembled after each heat (Gasik et al., 2009). The charge is loaded into the shaft (Fig. 4.25), located at the top of a sand bed with a space left (the receiver) for liquid metal.

There are also different types of hearth, such as tilting or water-cooled ones, for smelting of special ferroalloys and master alloys. The benefits of their use are simplicity and the possibility of processing melts with low impurities levels. However, the application of such off-furnace technologies is naturally limited to mixtures which can be exothermally reduced with a sufficient amount of heat being released. Sometimes they are combined with external heating or ignition by the top two or three electrodes.

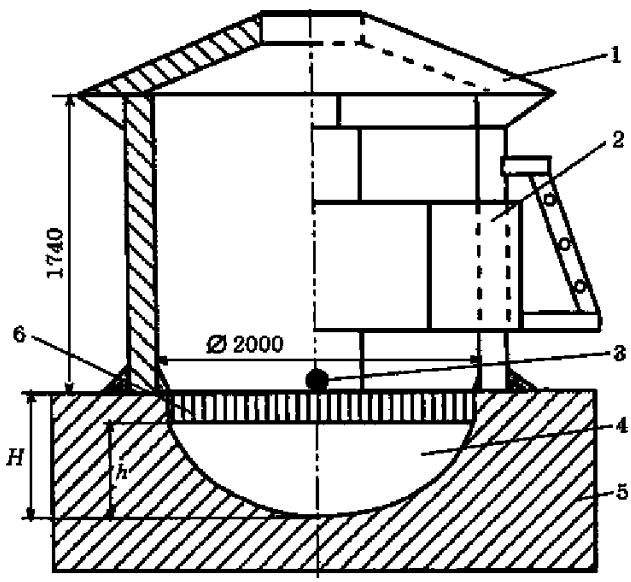

FIGURE 4.25 Smelting shaft for ferromolybdenum production. 1, shaft cover; 2, charge; 3, tapping hole; 4, metal ingot; 5, sand bed; 6, over-ingot slag; H, the height of the metal receiver; h, the height of the metal ingot. Dimensions are in mm. *(By permission of Gasik et al., 2009.)*

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