Kirk-Othmer Encyclopedia of Chemical Technology.

FURNACES, ELECTRIC, ARC FURNACES

Arc furnaces used in electric melting, smelting, and electrochemical operations are of two basic designs: the indirect and the direct arc. The arc of the indirect-arc furnace is maintained between two electrodes and radiates heat to the charge. The arcs of the direct-arc furnace are maintained between the charge and the electrodes, making the charge a part of the electrical power circuit. Not only is heat radiated to the charge, but the charge is heated directly by the arc and the current passing through the charge.

1. Indirect-Arc Furnaces

Indirect-arc furnaces have been used primarily in foundries for melting copper, copper alloys, and other nonferrous metals having a low melting point (see Copper). They have also been used for producing molten iron and, occasionally, molten steel (see Iron; Steel). The typical indirect-arc furnace is a single-phase furnace utilizing two horizontally mounted graphite electrodes, each of which project into an end of a refractory-lined horizontally mounted cylindrical steel shell. One electrode is set manually and the other electrode is automatically adjusted to maintain the preset voltage and current of the arc. The electrode pair is connected to a multivoltage tap transformer and reactor through flexible copper cables and bus bars.

Although rocking of the furnace to intermittently cover and hence protect up to 90% of the refractory, as well as improved refractories, has done much to make the indirect-arc furnace more viable, these furnaces are becoming less common, primarily due to high operating costs as a result of erosion of the refractory by the intense arc radiation.

2. Direct-Arc Furnaces

2.1. Open-Arc Furnaces

Most of the *open-arc furnaces* are used in melting and refining operations for steel and iron (Fig. 1). Although most furnaces have three electrodes and operate utilizing three-phase a-c power to be compatible with power transmission systems, d-c furnaces are becoming more common. Open-arc furnaces are also used in melting operations for nonferrous metals (particularly copper), slag, refractories, and other less volatile materials.

A standard melting furnace consists of a refractory-lined steel shell with water-cooled upper sidewalls and roof (the lower portion is refractory to contain the molten metal); graphite electrodes; electrical equipment, bus bars, and flexible conductors to energize the electrode(s) (Fig. 2); equipment to regulate the position of the electrodes and thereby control the energy input; a means to access the inside of the furnace through a door; a method to tilt the furnace to empty it; and a means to allow the furnace to be recharged. Practically all furnace shells are short vertical cylinders made of welded steel plate with reinforcing and water-cooled segments. The bottom usually is comprised of a steel dished head so that the refractory bottom lining can form an inverted

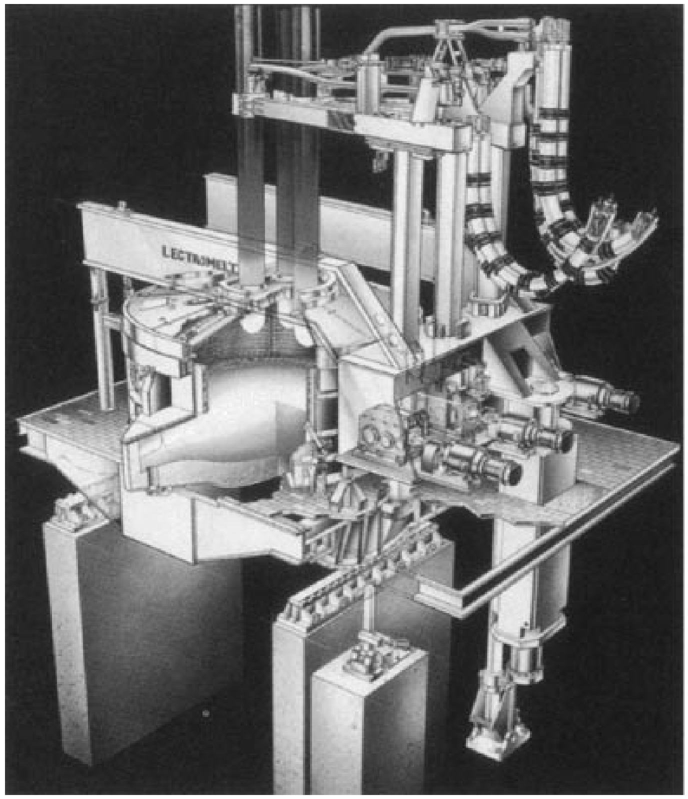

Fig. 1. A cut-away schematic of a typical a-c open-arc, steelmaking, eccentric bottom tapping (EBT) furnace. Courtesy of Lectromelt Corp.

arch to ensure the refractory's integrity. The dished bottom also results in a more even heat flux and allows the hearth to expand and contract freely with temperature changes but without overstressing the refractories.

Many shells are horizontally split to facilitate refractory repairs so that the nonproductive furnace time required to replace these refractories is minimized (1). Tapered shells are sometimes used to increase the charge capacity or hot metal capacity of existing furnaces. The conventional furnace shell contains a tapping spout to direct the molten contents when the furnace is emptied. More recently furnaces are being designed for eccentric bottom tapping (EBT) as shown in Figure 1. This design, where the tap hole is contained in the bottom of an extension to the furnace shell, allows the furnace to be completely drained by tilting the furnace only 15° as opposed to 45° for conventional furnaces. This allows a larger portion of the furnace sidewall to be water-cooled, which lowers refractory consumption. It also allows faster tapping and hence lower temperature losses during tapping. A water-cooled door is located diametrically across from the tap hole for the addition of alloys, fluxes, oxygen injection, etc, and allows the removal of slag. Additional openings are used on some furnaces to facilitate gunning, ie, spraying granular refractory material to rebuild the eroded lining; oxygen injection; or the introduction of oxy-fuel burners as a supplementary heat source.

The roof, in the form of a dome, is either comprised of refractory brick held in place by a water-cooled steel roof ring, or it may be composed of water-cooled panels. Sometimes water-cooled rings or glands are placed on the roof around the electrodes to maintain the refractory. On high power furnaces refractory is used around the electrodes to minimize the possibility of electrical short circuits.

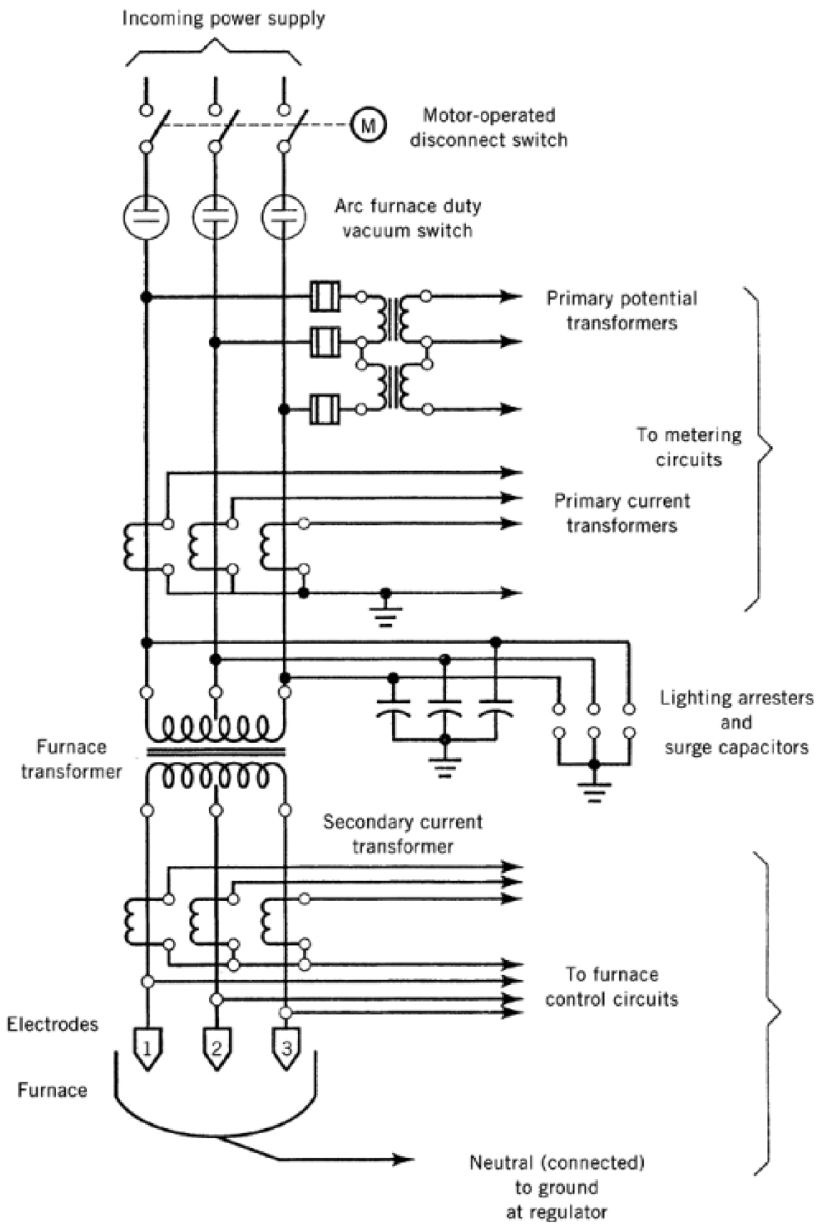

Fig. 2. Three-phase direct-arc furnace schematic.

2.1.1. Refractory Linings

The refractory linings (2, 3) for the hearth and lower walls of furnaces designed for melting ferrous materials may be acidic, basic, or neutral (see Refractories). Silica has been widely used in the past, and is still being used in a number of iron and steel foundries. Alumina, a neutral refractory, is normally used for furnace roofs and in the walls for iron foundries, but basic brick can also be used in roofs (4).

Magnesite or dolomite, basic refractories, are used primarily in furnaces where the sulfur or phosphorus content of the metal, or both, must be reduced. Usually the bottom is lined with one or more courses of refractory brick in either an inverted dome or stadium configuration to serve as a safety lining. Compatible granular material is rammed over the safety lining until the desired bottom contour is attained. For fully refractory-lined furnaces, the wall is lined with compatible brick. For basic lined furnaces the slag line refractory often contains 10 to 20% added carbon and other metallic additives to enhance the thermal conductivity and decrease the reactivity of the refractory to increase its service life. Insulating brick is not used because it increases the rate of refractory consumption by shifting the isotherms toward the furnace shell.

Acid linings are the least expensive linings and are used wherever the melting process allows it. However, their use often requires careful selection of the charge materials to minimize residual element concentrations, and acid refractories are subject to spalling and thermal damage. Therefore, a more expensive lining may be more economical in an intermittent operation. In this case fireclay and linings containing a higher percentage of alumina are used, or, as in most cases, basic practice is adopted for an overall lower cost operation.

Water-cooled cast or fabricated panels (5, 6) are popular and are used to replace up to 95% of the wall and roof refractories above the sill or slag line for EBT furnaces and 75% for conventionally designed furnaces. Energy consumption per ton of melt with water-cooled panels is generally the same as refractory linings. The typical life of the refractory walls and roofs in ferrous melting furnaces ranges from 200 cycles (heats) and can be greater than 1000 cycles, especially with patching or gunning, or both. In ultrahigh power furnaces (2000 kW/m^2 hearth area), the refractory life may be substantially reduced; thus special operating practices such as using foamy slags (7) are integral to the success of the arc furnace operation. The use of water-cooled panels has extended wall life to 1500 cycles, or more. The refractory hearth usually lasts at least six months and up to five years or more because it can be patched easily between cycles. As of the early 1990s, inert gas stirring through porous refractories or tuyeres in the hearth is being practiced. Energy and alloy savings are being claimed as well as increased yields due to improved slag/metal mixing.

2.1.2. Uses

The standard three-phase arc furnaces are available in sizes from 200 kg to 500 t and shell diameters of 1–12 m. Furnace transformer ratings are available from 200 to $>160,000$ kVA. The power density of steelmaking furnaces has gradually increased to the point at which extra ultrahigh power furnaces exhibit power densities in excess of 3500 kVA/m^2 of hearth.

Nearly all open-arc furnaces used in foundries and steel mills are three-phase and contain individually controlled jib-type electrode arms, each supporting a vertical column of graphite electrodes. The electrode arms are raised or lowered to maintain the desired arc characteristics, arc voltage, and current. This action takes place within a fraction of a second after the error signals are generated; the speed of the movement depends on the strengths of these signals as does the distance traveled. Each electrode arm is moving almost constantly because its arc characteristics are changing continually as scrap falls away from or against the electrodes, as the electrodes erode, as the atmosphere in the furnace changes, etc. Each electrode arm's electrical conductors are connected through flexible cables to the bus bars or tubes of the delta closure extensions and onto a multivoltage tap transformer. Generally, smaller furnace transformers (<7500 kW) and some larger transformers also contain a multitap reactor to provide sufficient inductive reactance to offset the negative characteristic of the arc so as to provide the desired arc stability.

2.1.3. Electrodes

Almost all the electrodes (8, 9) used in open-arc furnaces are prefabricated and are made of regular or dense graphite. Carbon electrodes seldom are used in melting furnaces, and those that are used are being replaced by graphite electrodes because of the latter's higher conductivity, lower weight, and smaller diameter which results in a smaller diameter electrode circle for a given size transformer. This increases the distance between the refractory wall and the arc which generally improves refractory life. Dense graphite electrodes are used instead of regular density electrodes whenever greater mechanical strength or slightly higher density, and accordingly conductivity, is required. Dense graphite electrodes are available in diameters of 32–762 mm. Regular density electrodes are commercially available in sizes of 178–610 mm diameter. With the advent of higher power d-c furnaces the pressure to increase the range of high density electrode sizes available has increased; thus electrodes up to 914 mm may be commercially available in the near future. Carbon electrodes are usually rated at electric current densities of 4.5–9 A/cm^2 and graphite electrodes at 15.5–46.5 A/cm^2.

The electrode diameter normally is selected on the basis of its current-carrying capability and its mechanical strength. The principal cause of electrode consumption usually is oxidation because of the high furnace temperatures and oxidizing furnace atmosphere. This oxidation rate is further accelerated by the electrode's surface temperature being increased by passage of current. Another factor is the stress that is imposed on the electrode by tilting the furnace, swinging the electrodes aside, scrap falling against the electrode, arc forces, etc.

Electrode consumption for ferrous melting a-c furnaces usually averages 2.5–6 kg/t of molten metal dependent on the particular furnace practices. D-c furnaces have electrode consumptions that are about 30% lower for similar operations. A typical energy consumption for a typical high productivity ministeel mill practice is 400 $kW{\cdot}h/t$. In comparison, power consumptions exceeding 600 $kW{\cdot}h/t$ in foundries is not unusual because of longer furnace cycle times.

2.1.4. Voltage

The voltage chosen for open-arc furnaces must be high enough to compensate for the voltage drops caused by the resistance and inductance of the primary and secondary electrical circuits and still have the required power input available to sustain the arcs (10). In the smaller furnaces, the voltage must be high enough to penetrate any thin oxide coatings on the scrap. Also, it must provide a sufficient area of meltdown; otherwise, the electrodes bore a small hole through the scrap, melting insufficient metal to cover the hearth resulting in high consumption of the bottom refractories. The highest phase-to-phase no-load voltage for a 200 kVA production furnace usually is 200 V, and 1000 V for a 120,000 kVA furnace is not uncommon. Lower voltages are also available for the operator to use during a furnace refining cycle; the lowest voltage is approximately one-third of the highest voltage. However, high productivity operations generally do not make use of the lower voltage taps.

For a given voltage tap, the operating electrode current can be <20 to $>100\%$ of the rated current depending on the quality of the electrode regulator and positioner. The current also reaches zero when there is no arc, because the electrode is too far from the charge, and maximum when the scrap falls against two electrodes and causes a short circuit. The power factor and arc voltage are highest at very low currents, whereas the maximum power input is attained at a power factor slightly higher than 0.707 (the cosine of 45°) depending on the electrical characteristics of the primary and secondary circuits. However, maximum power input does not necessarily equate with maximum efficiency (11). Typical operating power factors range from 0.68 to 0.82.

2.1.5. Vacuum-Arc Furnace

Another type of open-arc furnace is the *vacuum-arc furnace* (12) which is used for melting metals that have high temperature melting points, eg, titanium, molybdenum, and tungsten, or for upgrading alloy steels (Fig. 3). An electrode of the material to be melted is cast or formed from metal powder. An arc is formed between the starter button, B, and the electrode, E. As the electrode is melted, an ingot is formed in the water-cooled copper or steel mold, M. The furnace or mold cavity usually is under a vacuum, but it may also be filled with an inert gas. In some instances, a water-cooled tungsten-tip electrode is used and the material to be melted is dropped into the melting chamber and the rate of feed is coordinated with the power input.

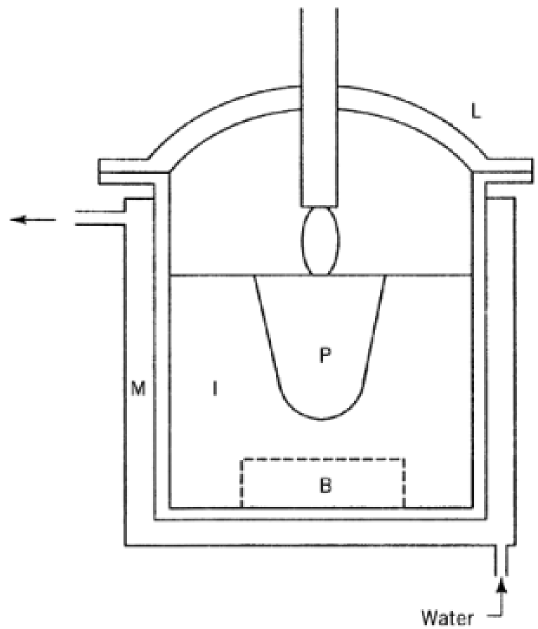

Fig. 3. Consumable-electrode melting in the vacuum-arc furnace (13). A, arc; B, button; E, electrode; I, ingot; L, lid; M, water-cooled mold; and P, pool of molten metal.

2.1.6. Plasma-Arc Furnace

The *plasma-arc furnace*, sometimes used in the production of castings of high alloy steels and special alloys or for the smelting of fine materials, usually has a furnace shell similar to that of the three-phase conventional open arc-furnace used in the production of iron, steel, or ferroalloys. However, water-cooled nonconsumable electrodes are used to conduct direct current and argon (to serve as the plasma base) to the sealed furnace interior. The plasma torch can be of either the transferred or nontransferred type. The two types are distinguished by the electric current conduction path. There, most commonly, are one (14) or more (15) fixed electrodes in the furnace roof or sidewall and a water-cooled bottom electrode extending through the refractory hearth so that it is in contact with the molten metal serving as the anode. It is said that the increased operating costs for argon and refractories are compensated for by the savings in alloy and graphite electrodes, but inherent longer arcs in plasma furnaces, if not properly contained, may reduce efficiency.

As with a plasma-arc furnace, various gases and pneumatically conveyed solids have been added to the various types of a-c open-arc furnaces to decrease alloy loss, to stabilize the arc, and to decrease the noise level, but with mixed commercial success.

2.2. D-C Arc Furnace

With the advent of more economical thyristor-controlled d-c power supplies, as well as limitations imposed by power companies on arc furnace-generated flicker, d-c furnaces (16) have become more common, particularly in countries with weak power grids such as Japan. These furnaces are nearly identical to their counterparts, except they typically have a single electrode passing through the roof and a means to collect the current through a furnace bottom electrode. Bottom electrode designs include full conductive bottoms and electrodes, made of various conducting materials, that protrude through the refractory to make contact with the melt. The latter type generally includes some water-cooled parts under the furnace.

Due to their similarity to a-c furnaces, *d-c furnaces* can be substituted for nearly any a-c furnace including the open-arc, submerged-arc, and arc-resistance furnaces, provided that design criteria, particularly electrical parameters, are properly chosen. Currently, steel and ferrochrome is being made commercially in d-c furnaces and a silicon metal pilot plant is being built.

There are substantiated claims that d-c furnaces exhibit advantages in power consumption, graphite consumption, noise, and power transmission line disturbance. Initially these may be offset by a slightly higher initial cost for these furnaces. In addition, production from a d-c furnace is claimed to be higher than a comparable a-c furnace, however, the required periodic bottom electrode maintenance may negate this gain over longer time periods.

2.3. Submerged-Arc Furnace

Furnaces used for smelting and for certain electrochemical operations are similar in general design to the open-arc furnace in that they are usually three-phase, have three vertical electrode columns and a shell to contain the charge, but direct current may also be utilized. They are used in the production of phosphorus, calcium carbide, ferroalloys, silicon, other metals and compounds (17), and numerous types of high temperature refractories.

When a smelting campaign is started, carbonaceous material, eg, coke or a conductive material, is placed on the hearth. The electrodes are lowered and arc on this material is at a low power input. The charge materials (ores, reductants, etc) are added slowly. As the material becomes molten and conductive, the power input and charging rate are correspondingly increased to the desired production rate when the furnace is filled with the charge materials. The electrodes continue to arc on the pool of molten metal on the furnace hearth, and the furnace exhibits electrical characteristics similar to open-arc steelmaking furnaces which have an attendant current voltage phase shift. Submerged describes the operation in that the electrode tip is surrounded by charge material in different stages of melting or reduction. In the submerged-arc case, the space immediately beneath the electrode is filled with ionized gases through which the arcs travel, which is typical of silicon alloy production operations. These gases travel upward through the burden, preheating it, and burn at the top with open flames. Generally the gases are collected to separate toxic materials and/or to recover waste heat.

2.4. Arc-Resistance Furnace

The arc-resistance furnace is similar to the submerged-arc furnace except the electrodes of the former are most often in direct contact with material, usually slag or a nonmetallic material, but they may also arc to the slag layer. Even when the electrode is in contact with the melt there are still minute arcs between the bottom and sides of the electrode, because it is not wetted by the slag, and the majority of the heat is developed in the melt in the immediate vicinity of the electrode tip. The furnace interior may be filled with a burden of unmelted charge above the melt, as in a submerged-arc furnace, or may contain a bare molten bath. The primary difference between the arc-resistance and submerged-arc furnace is that the former exhibits ohmic conductance. Often the two types are confused and hence misnamed. Most of the submerged-arc and arc-resistance furnaces do not tilt and sometimes do not have roofs. Where the volatilized materials and gases are toxic or cannot be exposed to air, the shell is covered with a refractory roof or hood so that the gases and vapors can be ducted away from the furnace for subsequent collection.

Most furnace shells are short vertical cylinders but may also be triangular, elliptical, or rectangular in plan view. Single-phase furnaces may have one or two movable electrodes. Three-phase furnaces usually have three movable electrodes, but some have six (three pairs, two electrodes for each phase). This is more common for larger smelting furnaces used to produce ferronickel, ferromanganese, silicon, and copper mattes. A few of the smaller furnaces must tilt to expedite emptying a portion of the molten material since the transfer must be extremely rapid to keep the high melting point material from freezing. In cases of materials having melting

Table 1. Electrode[a] Consumption, kg/MW·h

standard ferromanganese	5.0
pig iron	5.0
75% ferrosilicon and silicon metal	6.0
aluminum silicon	15.0
calcium carbide	7.0
phosphorus	1.5
nickel matte	5.0

[a] Submerged arc furnace.

points over 2200°C, the vertical portion of the furnace shell may be removable to allow cooling of the materials for a day or two. After cooling, the fused material can be broken into smaller pieces for further processing and the nonfused material can be added to the next furnace charge. Generally, these furnaces have a refractory lining. When there is no appropriate refractory material to withstand the high temperature and the chemical reaction with the material to be processed, then unmelted material is used for lining the furnace. In other instances, the shell is cooled by water sprays to freeze the melt, thus utilizing a self-lining concept.

2.4.1. Electrodes

Because of the numerous different processes, there are many different types of electrodes in use (9), eg, prefabricated graphite, prefabricated carbon, self-baking, and composite electrodes (see Carbon). Graphite electrodes are used primarily in smaller furnaces or in sealed furnaces. Prebaked carbon electrodes, made in diameters of <152 cm or 76 by 61 cm rectangular, are used primarily in smelting furnaces where the process requires them. However, self-baking electrodes are preferred because of their lower cost.

The self-baking electrode (8–18) consists of a cylindrical steel casing that has internal radial fins. These casings are periodically filled with a carbonaceous paste. As the electrode is consumed and automatically lowered, the heat from the furnace and the electrical current passing through the electrode softens and subsequently bakes the carbonaceous paste to form a solid, monolithic mass. New sections of casing are welded on as the electrode is consumed. Self-baking electrodes having diameters of <165 cm are used on numerous types of ferroalloy furnaces when the process can tolerate the iron impurity (see also Aluminum and aluminum alloys). Testing has been performed on iron-free self-baking electrodes, but they have not yet become commercially accepted. Electrodes over 165 cm are seldom used because the skin effect of a-c current prevents proper utilization of such a large conductor.

A typical large three-phase ferroalloy furnace using prebaked carbon electrodes is shown in Figure 4. The hearth and lower walls where molten materials come in contact with refractories are usually composed of carbon blocks backed by safety courses of brick. In the upper section, where the refractories are not exposed to the higher temperatures, superduty or regular firebrick may be used. The walls of the shell also may be water-cooled for extended life. Usually, the furnace shell is elevated and supported on beams or on concrete piers to allow ventilation of the bottom. When normal ventilation is insufficient, blowers are added to remove the heat more rapidly. The shell also may rest on a turntable so that it can be oscillated slightly more than 120° at a speed equivalent to 0.25–1 revolution per day in order to equalize refractory erosion or bottom buildup.

The larger electrodes are usually supported from overhead by chains, cables, or steel bands connected to a regulating winch or hydraulic cylinders. Alternatively, the columns may be supported directly by hydraulic cylinders. The electrodes are often held in alignment by insulated vertical guides. The arcs are quite stable because of the atmosphere in the arcing zone that allows the use of slower yet more sensitive regulators and positioners as compared to steelmaking furnaces.

Table 1 shows some of the typical electrode consumption figures for various submerged-arc furnace operations.

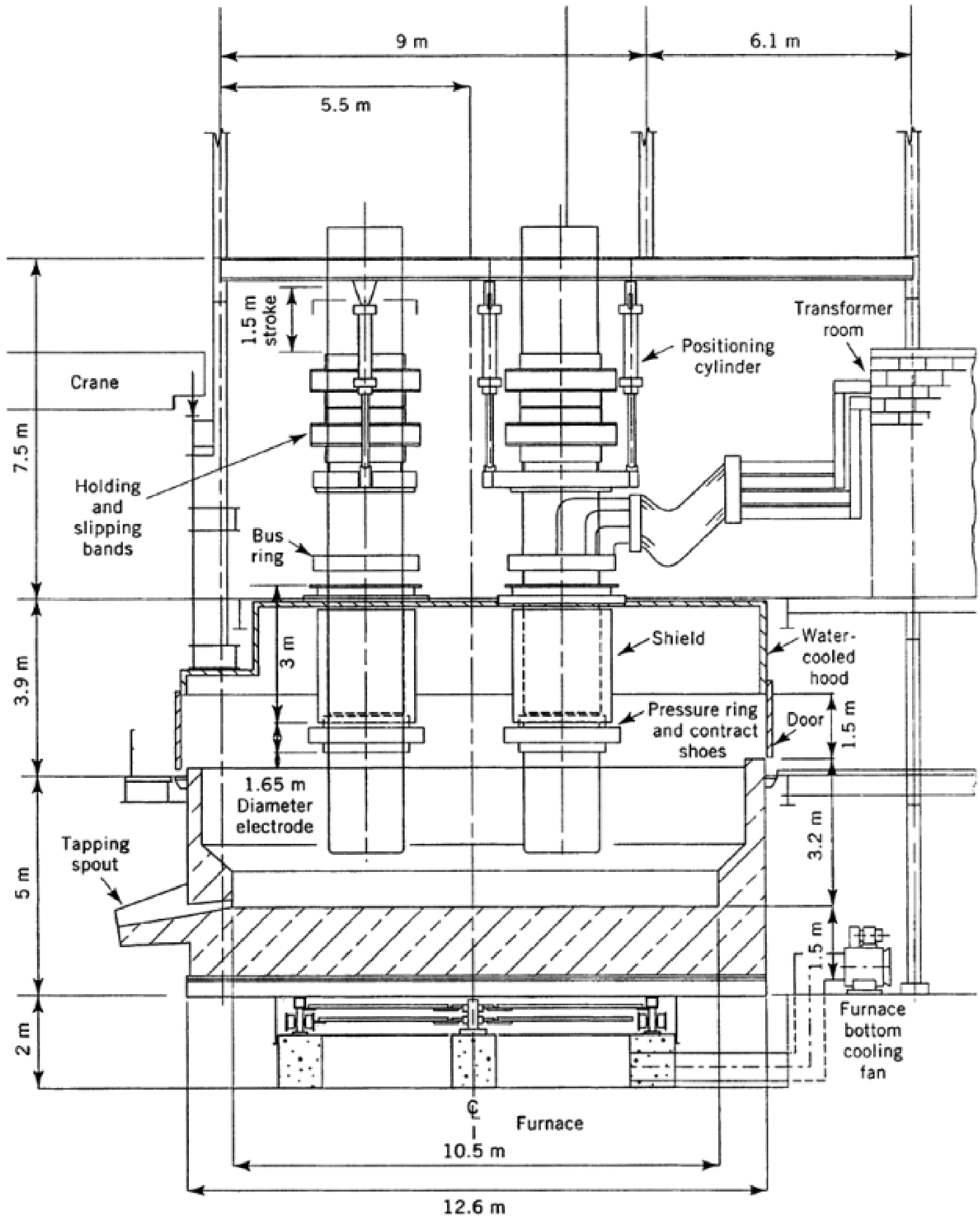

Fig. 4. Design of a ferroalloy furnace.Courtesy of Lectromelt Corp.

Energy consumptions for submerged-arc and arc-resistance furnaces are generally higher than for open-arc furnaces, because the latter is used primarily for melting and refining metals. In contrast, the submerged-arc and arc-resistance furnaces are used in melting of compounds, eg, ores, slags, etc, that have much higher specific heats. Furthermore extra energy must also be furnished to allow the desired endothermic reactions to proceed to completion. Therefore, in a reduction operation, energy consumption figures can vary from 700 to over

$13,000\ \mathrm{kW{\cdot}h/t}$ of product, depending on the materials to be processed and the product desired. In submerged-arc and arc-resistance furnaces, the powering, furnace size, electrode size, electrode spacing, diameter–height ratio of the lined shell, voltage, and current are critical factors that must be closely coordinated to optimize energy consumption, electrode consumption, and furnace production (19–21).

3. Health and Safety

Because intense heat is generated in these furnaces it is understandable that the arc volatilizes such metals as tin, zinc, lead, cadmium, and the like. In addition, both melting and smelting furnaces may generate large amounts of carbon monoxide. As a result all new furnace installations require pollution control equipment. This normally consists of off-gas afterburning (sometimes with energy recovery), and dust collection equipment, typically a baghouse. Most dusts collected are considered hazardous wastes because of their heavy-metal content and accordingly must be treated and/or disposed of in a prescribed manner.

For arc furnace worker safety, high power electrical systems require proper design and precautions, and handling of molten materials requires a minimum of fire-retardant clothing and often dust masks. Water must be prevented from coming in contact with the melt. Furthermore, since open-arc furnace noise levels commonly exceed 100 dBA, hearing protection is a necessity. Noise is normally not a problem with smelting furnaces.

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