FURNACES, ELECTRIC

1. Introduction

The term electric furnace applies to all furnaces that use electrical energy as their sole source of heat. The definition distinguishes such apparatus from traditional fuel-fired furnaces (see FURNACES, FUEL-FIRED) in which heat is produced directly by combustion of fossil fuels (eg, coal, oil, or gas). Electric furnaces are used mainly for heating solid materials to desired temperatures below their melting points for subsequent processing, or melting materials for subsequent casting into desired shapes, ie, electric heating furnaces or electric melting furnaces. The latter includes so-called holding furnaces which store a molten charge received from separate melting furnaces.

Classification is by the manner in which the electrical energy is converted into heat. Thus three distinct types of widely used industrial furnaces can be distinguished: electric resistance furnaces, electric arc furnaces, and electric induction furnaces. The conversion of electrical energy into heat in each type of furnace is schematically illustrated in Figure 1. Common to all is a charge that is to be heated or melted, A, a refractory furnace lining, B, and an electric power supply, C. The refractory lining separates the hot furnace interior from the work area. It must withstand high temperatures and provide thermal insulation to conserve energy. The lining is often contained in a steel structure. The power supply is normally ac (dc is rarely used) at standard power line frequency (60 Hz in North America) and it usually includes a transformer so that the most

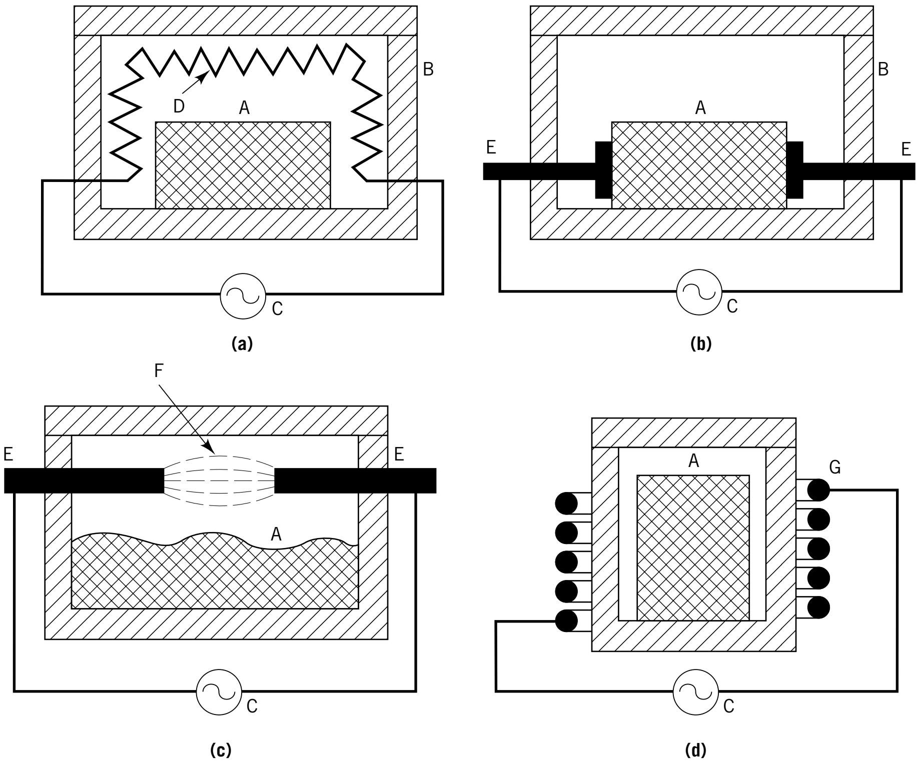

Fig. 1. Main types of electric furnaces: (**a**) resistance furnace, indirect heat (resistor furnace); (**b**) resistance furnace, direct heat; (**c**) arc furnace; (**d**) induction furnace. A, charge to be heated or melted; B, refractory furnace lining; C, electric power supply; D, resistors; E, electrodes; F, electric arc; G, induction coil.

suitable furnace voltage is obtained. However, certain induction furnaces require a higher frequency.

2. Resistance Furnaces

The most widely used and best known resistance furnaces are indirect-heat resistance furnaces or electric resistor furnaces. They are categorized by a combination of four factors: batch or continuous; protective atmosphere or air atmosphere; method of heat transfer; and operating temperature. The primary method of heat transfer in an electric furnace is usually a function of the operating temperature range. The three methods of heat transfer are radiation, convection, and conduction. Radiation and convection apply to all of the furnaces described. Conductive heat transfer is limited to special types of furnaces.

Operating temperature ranges are classified as low, medium, and high; there is no standard or precise definition of these ranges. Generally, a low temperature furnace operates below 760°C, medium temperature ranges from 760–1150°C, and furnaces operating above 1150°C are high temperature furnaces. There is often indiscriminate use of the words furnace and oven. The term oven should be used when temperatures are below 760°C, and the word furnace applied for higher temperatures. The term furnace is used here regardless of operating temperature.

2.1. Batch Furnaces. In batch furnaces the desired time–temperature cycle for the product to be processed is accomplished by subjecting the entire furnace and its contents or charge of work to the particular cycle. Batch furnaces are most often used for very large and/or heavy charges, low production rates, infrequent operation, variable time–temperature cycle, and processing material that must be in batches because of previous or subsequent operations. Larger batch furnaces are often of the elevator or car-bottom type. In this furnace, the charge of one or many pieces is loaded onto the hearth of a car. The car is moved under the furnace and is hoisted into the furnace by way of an elevator mechanism which is part of the furnace. Very large or heavy loads are often processed in a car-bottom furnace similar to the elevator furnace except that the furnace is not elevated and the car carries the work into the furnace through a door at one end.

Medium-sized loads are often processed in a bell furnace, as shown in Figure 2. The operation of this furnace is opposite to that of an elevator furnace:

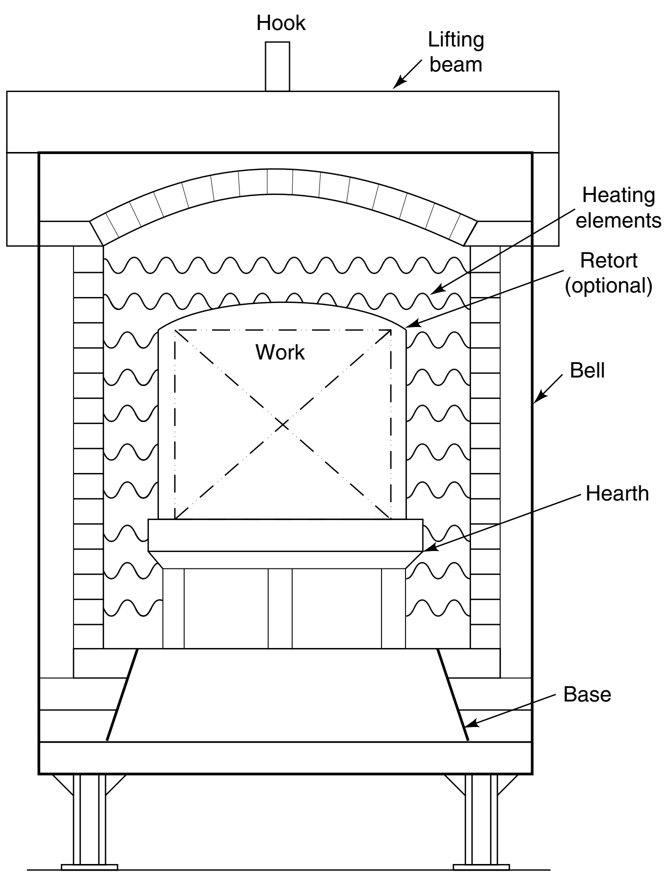

Fig. 2. Typical electric bell furnace.

the work load is placed on a stationary hearth and the furnace is lowered over the hearth. Bell furnaces are often arranged with two or more bases (hearths) which permit more efficient use of the furnace because one base can be unloaded/loaded as the furnace carries out a heating cycle on another base.

Small loads are commonly processed in a box furnace. The product is placed on the furnace hearth through a door. Box furnaces may be single-ended or double-ended. A single-ended box furnace is usually used in an air atmosphere application where the product can be removed hot from the furnace for cooling. A double-ended box furnace is usually used in a controlled atmosphere application. In this case a water cooler is attached to one end. The product can be placed on the hearth (in the heat chamber) through the front door, then after the product reaches temperature, it is manually transferred into the water cooler for cooling before it is manually removed out the exit door on the other end of the water cooler.

Other versions include the pit furnace, which is a box furnace with the door on top and which is often installed in a pit with the top of the furnace near floor level.

2.2. Continuous Furnaces. These furnaces are applicable for uniform charges of work that arrive at the furnace continuously, moderate to high production rates, constant time–temperature cycle, and continuous operation over at least one and preferably two or three shifts per day. The desired time–temperature cycle is designed into the continuous furnace. The charge is subjected to this cycle by moving it through chambers operating at different temperatures. Although temperatures may be varied, a sequence, eg, heat, cold, and cool, is a part of the furnace design, and it may be difficult and expensive to change this cycle once the furnace is built. Although multicycle continuous furnaces are possible, they are expensive and are subject to design limitations. Continuous furnaces are usually named for the method used to convey the material through the furnace.

The roller-hearth furnace shown in Figure 3 is used to process a wide variety of parts. Unless the configuration of the work permits it to roll on a roller conveyor, the charge is carried on a tray or, in the case of small parts, in a basket which is in turn carried by a tray. For any given operating temperature, the weight that can be carried per unit length of the furnace is limited by the strength of the rolls.

Light loads are often processed in a mesh-belt furnace which usually carries the work load directly on the mesh belt. At a given operating temperature, loading per unit area of the belt is limited by its tensile strength. Cast-link belt furnaces function in the same manner as mesh-belt furnaces except that the former carry heavier loads because the belt is made from suitable alloy castings instead of woven wire. The belt is normally contained in the furnace on both the working and return sides, whereas the mesh-belt usually exits the furnace with the work load and returns outside the furnace. Because of its large weight, it is uneconomical to let the cast-link belt cool on the return and reheat it with the work load.

In pusher furnaces, the product (work load) is pushed through the furnace in steps by a hydraulic or electromechanical mechanism that pushes each load into the furnace, thus pushing all work in the furnace ahead one work space. The walking-beam furnace lifts the work load on a walking beam, advances

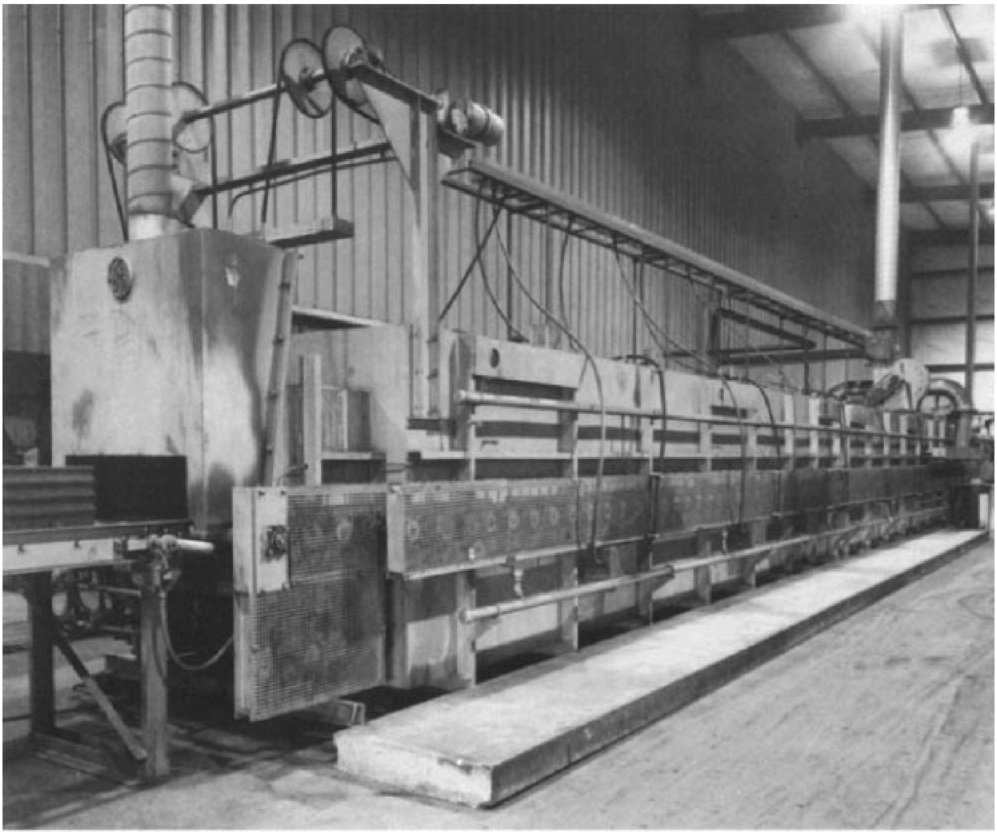

Fig. 3. Roller-hearth furnace. (Courtesy of Wellman Furnaces, Inc.)

the load a step, and returns the work to the hearth. The walking beam then returns to its original position (under the hearth) in preparation for the next step.

2.3. Furnace Atmospheres. Electric furnaces can operate either with air in the interior of the furnace or with a protective atmosphere; the choice is dictated by the process requirements of the work. The furnace must be designed for the atmosphere to be used, because the combination of temperature and atmosphere are significant factors in selecting internal materials used in the furnace construction; this applies particularly to the selection of heating element (resistor) material. It is feasible and common to design an electric furnace that can operate in both air and protective atmospheres although shortened element life generally results from frequent alternating between reducing atmospheres and oxidizing atmospheres. There are exceptions to this rule as some resistor materials must be periodically oxidized, if used in a reducing atmosphere. Other resistor materials are limited to a particular atmosphere.

Air-Atmosphere Furnaces. These furnaces are applied to processes where the work load can tolerate the oxidation that occurs at elevated temperatures in air. In some special applications, the oxidation is not only tolerable but is desired. Some furnaces heat the work solely to promote oxidation. Furnaces designed for air operation are not completely gas-tight which results in somewhat lower construction costs. There are no particular problems encountered in selecting the insulation systems because almost all refractory insulations are made up of oxides. Heating element materials are readily available for the common temperature ranges used with air atmospheres.

Protective-Atmosphere Furnaces. These furnaces are used where the work cannot tolerate oxidation or where the atmosphere must provide a chemical or metallurgical reaction with the work. In some cases, mainly in high temperature applications, the atmosphere is required to protect the electric heating element from oxidation.

Protective-atmosphere furnaces are of two general types. In one type, the work is inside a muffle (retort) and the protective atmosphere is inside the muffle. The outside of the muffle and the interior of the furnace operate in air and are designed accordingly. The other type is gas-tight, and the atmosphere is introduced directly into the furnace, obviating the expensive and expendable retort or muffle. It does require careful selection of the internal furnace parts which must not be adversely affected by the atmosphere. The selection of electric heating elements must be carefully made with respect to operating temperature and atmosphere. The best material to use for a given application is a function of the combination of temperature and atmosphere.

The true operating temperature range and atmosphere must be specified in a description of an electric controlled-atmosphere furnace. Frequently, a higher temperature is specified than required for the contemplated operations, apparently with the thought that the higher temperature construction results in a safety factor. In the case of heating elements it can result in more expensive materials which, at the true operating temperature, are actually inferior to less expensive element materials. In addition to heating elements, there are other materials used in furnace construction that are satisfactory for one temperature range but are not suitable for a lower temperature operation.

2.4. Low Temperature Convection Furnaces. Low temperature convection furnaces are designed to transfer the heat from the heating elements by forced convection. Convection is normally used in furnaces operating below 760°C because it is the most effective means of heat transfer that can maintain good uniformity of temperature on various workload configurations. Convection furnaces also are used (in this range of temperatures) where it is important that no part of the work load exceed the controlled temperature. This is accomplished by shielding the work load from any view of the heating elements and by controlling the temperature of the air or atmosphere, which carries the heat from the heating elements to the work, at the desired maximum temperature.

One design for a low temperature convection furnace shown in Figure 4 utilizes an external circulating fan, heating chamber, and duct system. The fan draws air (or a protective atmosphere) from the furnace and passes through the external heating chamber and back into the furnace past the work. This system minimizes the chance that the work receives any direct heat radiation. In theory it is less efficient because the external blower, heating chamber, and ductwork add external surfaces that are subject to heat losses.

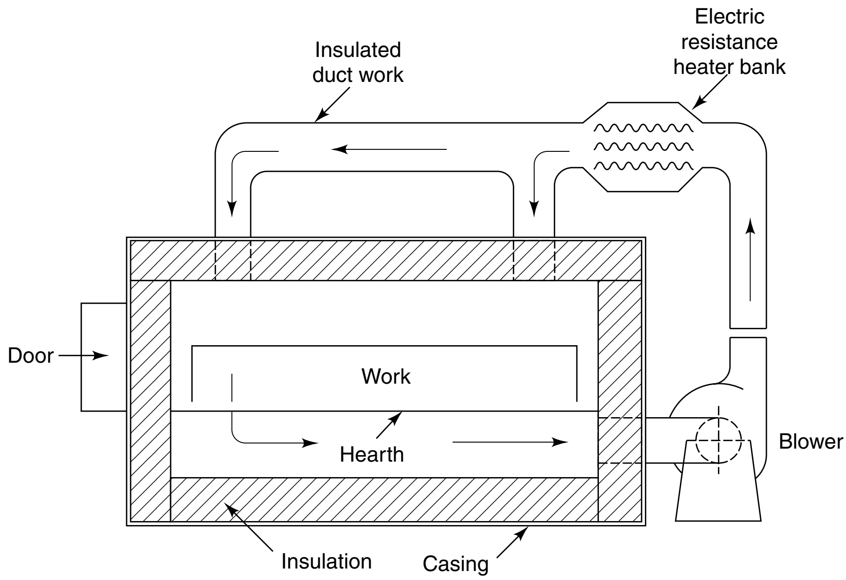

Fig. 4. External heating chamber convection furnace.

Another design, shown in Figure 5, functions similarly but all components are inside the furnace. An internal fan moves air (or a protective atmosphere) down past the heating elements located between the sidewalls and baffle, under the hearth, up past the work and back into the fan suction. Depending on the specific application, the flow direction may be reversed if a propeller-type fan is used. This design eliminates floorspace requirements and eliminates added heat losses of the external system but requires careful design to prevent radiant heat transfer to the work.

Heating elements operating $<760^{\circ}$C are almost always of a chrome–nickel resistance alloy and are in the form of ribbon, cast alloy, open wire coils, or sheathed construction. Several alloys are suitable in this temperature range and all are satisfactory if properly applied. In general, the more expensive alloys are used when physical space limitations dictate higher watts per area dissipation from the element.

2.5. Radiation Furnaces. *Low Temperature Radiation Furnaces.* These are of the infrared heater type. Heat transfer is by direct radiation from a high temperature heating element. Control of the heat is obtained by controlling the time of exposure to the heat radiation. This type of furnace is normally used for such applications as drying of paint films. Heating elements are nickel–chrome resistance wire which is wound on ceramic supports or contained in sheaths. Other materials include tungsten resistors in glass or quartz envelopes which exclude oxygen from the resistors.

Medium Temperature Radiation Furnaces. The temperature range is generally 760–1150°C. Most of the heat is transferred directly to the work by radiation from the heating elements and by radiation to the furnace refractory which reradiates the energy to the work. Heating elements may be located in

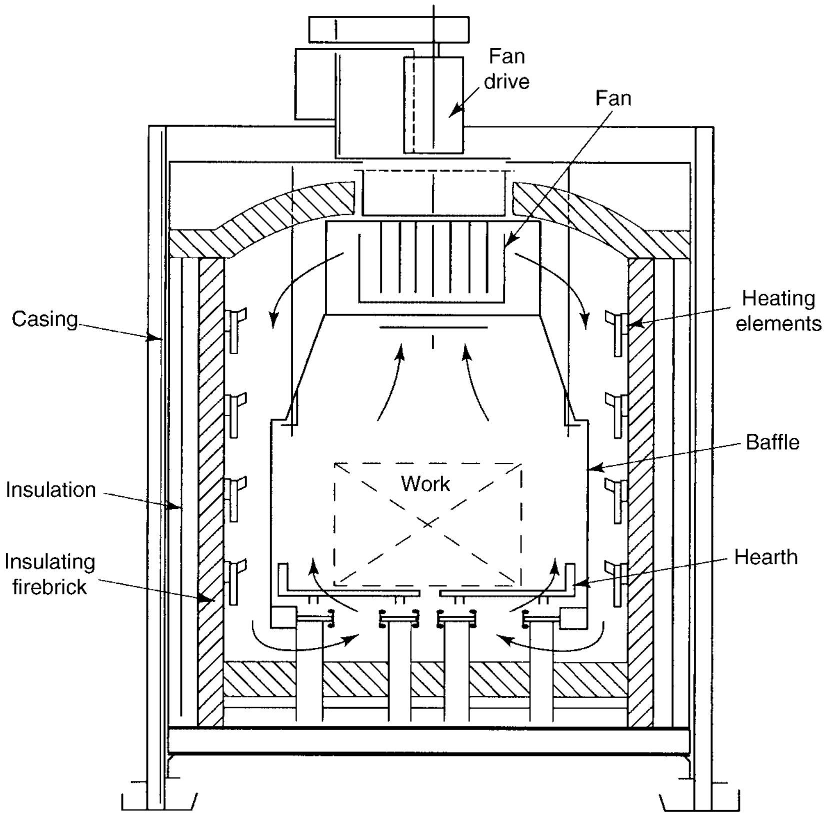

Fig. 5. Internal heating-element convection furnace cross section.

the sidewalls, roof, or floor of the furnace. Location of heating elements must be selected to assure uniform temperatures in the work zone. Elements located below the hearth level require protection from falling work or other contaminants. Figure 6 shows a typical cross section through a radiation furnace.

From 760 to 960°C, circulating fans, normally without baffles, are used to improve temperature uniformity and overall heat transfer by adding some convection heat transfer. They create a directional movement of the air or atmosphere but not the positive flow past the heating elements to the work as in a convection furnace. Heating elements are commonly chrome–nickel alloys in the forms described previously. Sheathed elements are limited to the very low end of the temperature range, whereas at the upper end silicon carbide resistors may be used. In this temperature range the selection of heating element materials, based on the combination of temperature and atmosphere, becomes critical (1).

High Temperature Radiation Furnaces. These furnaces are similar in construction to medium temperature radiation furnaces, but operate above 1150°C. The insulation system must be designed to withstand the high temperatures, and internal structural parts become critical.

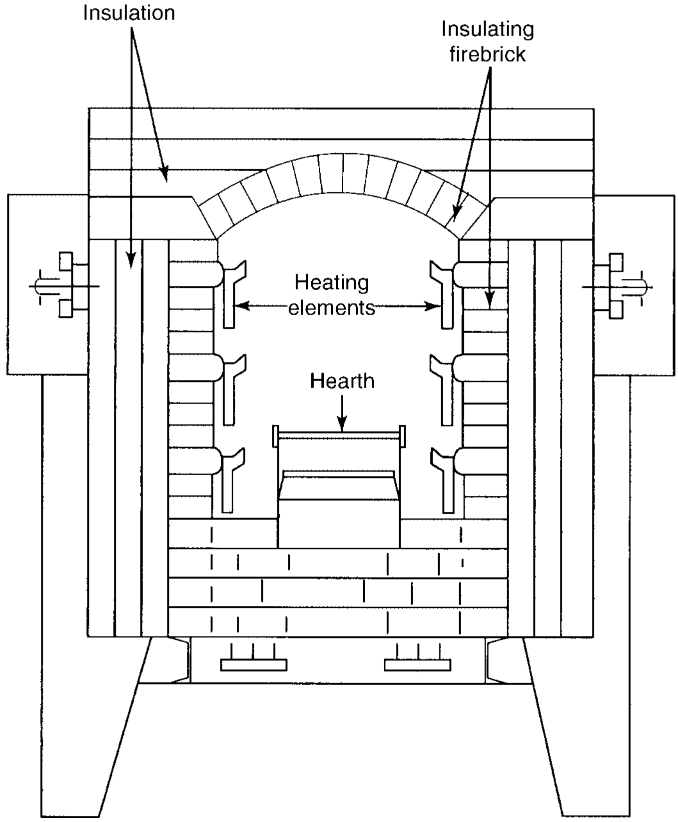

Fig. 6. Typical medium temperature radiation furnace cross section.

At temperatures above 1150°C, alloys used for the hearth or material handling systems in low and medium temperature furnaces lose strength rapidly (2) and temperatures are reached where ceramic refractories are required to support the work. This results in less use of roller-hearth and belt-type hearths and greater use of pushers or walking-beam designs for continuous furnaces.

Chrome–nickel alloy heating elements that commonly are used in low temperature furnaces are not suitable above the very low end of the range. Elements commonly used as resistors are either silicon carbide, carbon, or high temperature metals, eg, molybdenum and tungsten. The latter impose stringent limitations on the atmosphere that must be maintained around the heating elements to prevent rapid element failure (3), or the furnace should be designed to allow easy, periodic replacement.

Refractory selection becomes critical with high temperature radiation furnaces that have molybdenum or tungsten heating elements. Although these elements are stable in vacuum or inert atmospheres, many applications require a reducing atmosphere, often high in hydrogen content and very dry. In these cases, there is the possibility of reducing the oxides that make up refractory insulations. Published data are available relating temperature and dew point at which hydrogen reduces the various oxides present in insulations (4). If this point is reached, the reduction process begins to destroy the insulation system of the furnace, thus limiting the maximum practical operating temperature to less than the capability of the heating element material (see REFRACTORIES).

Vacuum Radiation Furnaces. Vacuum furnaces are used where the work can be satisfactorily processed only in a vacuum or in a protective atmosphere. Most vacuum furnaces use molybdenum heating elements. Because all heat transfer is by radiation, metal radiation shields are used to reduce heat transfer to the furnace casing. The casing is water-cooled and a sufficient number of radiation shields between the inner cavity and the casing reduce the heat flow to the casing to a reasonable level. These shields are substitutes for the insulating refractories used in other furnaces.

2.6. Conduction Furnaces. Conduction furnaces utilize a liquid at the operating temperature to transfer the heat from the heating elements to the work being processed. Some furnaces have a pot filled with a low melting metal, eg, lead, or a salt mixture, eg, sodium chloride and potassium chloride, with a radiation-type furnace surrounding the pot. Although final heat transfer to the work is by conduction from the hot lead or salt to the work, the initial transfer of heat from the resistors to the pot is by radiation.

Conduction furnaces are of three general types. One has a pot or crucible with suitable exterior insulation. Sheathed resistance elements are inside the pot which contains molten lead or another low melting metal. The molten metal can be the conductive medium that transfers heat to the work immersed in it, or the molten metal may be the work. Such furnaces are often used to supply molten-type metal, lead, zinc, etc. As the molten metal is removed, bars of the metal are added for melting. The initial charge of solid metal does not provide good surface contact with the heating elements and, because of this, the metal around the heating elements is often melted initially with a torch or other auxiliary heat during start up.

The salt-bath furnace is another type of conduction furnace. A molten salt not only provides the medium for conductive heat transfer, the salt is the heating resistor. These furnaces commonly are applied for temperatures ranging from slightly above the melting point of the salt to 1260°C. The salt-bath furnace shown in Figure 7 consists of a metal (or for higher temperatures, ceramic) crucible that is surrounded by a suitable insulating refractory and the outer casing. Metal electrodes immersed in the salt are connected to a low voltage power source. Placement of electrodes is important because the mean path through the salt determines the resistance of the salt which serves as heating resistor. The current should flow from electrode to electrode with a negligible amount of current passing through the work when it is immersed in the bath.

Cold sodium chloride, either granulated or solidified after melting, has a high electrical resistance and low heat conductance (See SODIUM COMPOUNDS). It is, therefore, necessary to make provisions for melting the initial charge of salt. This can be done by melting it in a radiation furnace and pouring the molten salt into the salt-bath furnace or by melting the salt in the salt-bath furnace with a torch. The torch method is necessary when a salt bath solidifies as a result of a planned maintenance shutdown or a prolonged power failure. If the shutdown is

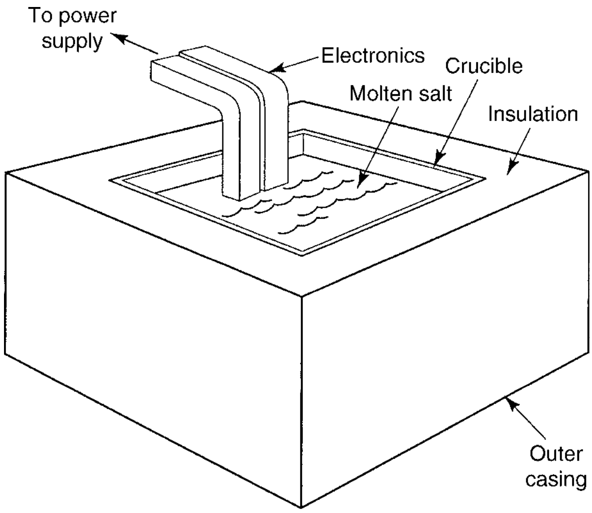

Fig. 7. Salt-bath furnace.

planned, heat conducting metal tubes can be placed in the bath to improve heat transfer when remelting the salt.

The third type of conduction furnace is a fluidized bed. In this design the product to be heated is submerged in sand, which is supported by a high porosity plate. Heated air (or atmosphere) is recirculated through the porous plate and sand, which gives a high heat-transfer efficiency to the product. The disadvantage of this furnace is the product usually has a lot of warpage. To correct this, fixturing usually is required, which means more mass needs to be heated. Fluidized-bed furnaces are usually used at low and medium temperature ranges; the higher the temperature the more maintenance is needed on the recirculating fan.

2.7. Direct-Heat Electric-Resistance Furnaces. Direct-heat electric furnaces use the material to be heated as the resistor, and the furnace consists of an insulated enclosure to retain the heat, a power source of suitable voltage, and means of attaching the power leads to the work (Fig. 8). This type of furnace has several limitations that have prevented widespread use. Since the work is the resistor, it must have a uniform cross section between power connection points, and the material must be homogeneous. Varying sections or nonuniformities in the material can produce hot or cold spots in proportion to the change in electrical resistance. Also, a given furnace must be designed for work in which each piece to be heated has about the same resistance and power requirements. Although voltage and power can be controlled, a furnace designed to heat a part with a given cross section and length probably does not have the voltage required to heat a part of twice the length and half the cross section or have the current capacity to heat a part of half the length and twice the cross section.

There are additional problems in making the electrical connections to the work to be heated. The connection must have low electrical resistance to prevent overheating at the point of contact, but such a connection has a low resistance to

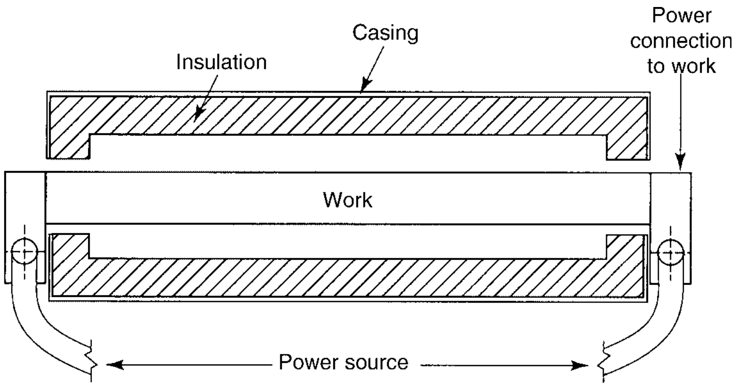

Fig. 8. Direct-heat resistance furnace.

heat transfer, thus conducting heat away from the work. These problems have limited the use of direct-resistance heating mainly to heating of pipe, tubing, bars, or small identical parts. This heating is a one-piece-at-a-time batch operation and often does not use an insulated housing; instead it is used as a preheater for a forming operation that takes place as soon as the work reaches the desired temperature.

There are large-scale operations using direct-heat resistance furnaces. These are mainly in melting bulk materials where the liquid material serves as a uniform resistor. The material is contained in a crucible of fixed dimensions which, coupled with a given resistivity of the material, fixes the total resistance within reasonable limits. The most common application for this type of direct-heat electric resistance furnace is the melting of glass (qv) and arc furnaces for the melting of steel (qv).

3. 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.

3.1. 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

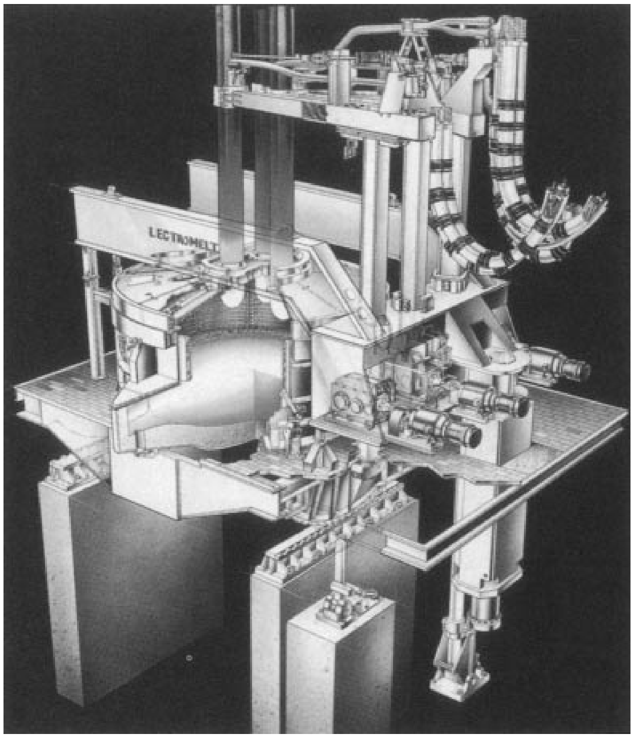

Fig. 9. A cut-away schematic of a typical a-c open-arc, steelmaking, eccentric bottom tapping (EBT) furnace. (Courtesy of Lectromelt Corp.)

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.

3.2. Direct-Arc Furnaces. *Open-Arc Furnaces.* Most of the open-arc furnaces are used in melting and refining operations for steel and iron (Fig. 9). 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. 10); 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;

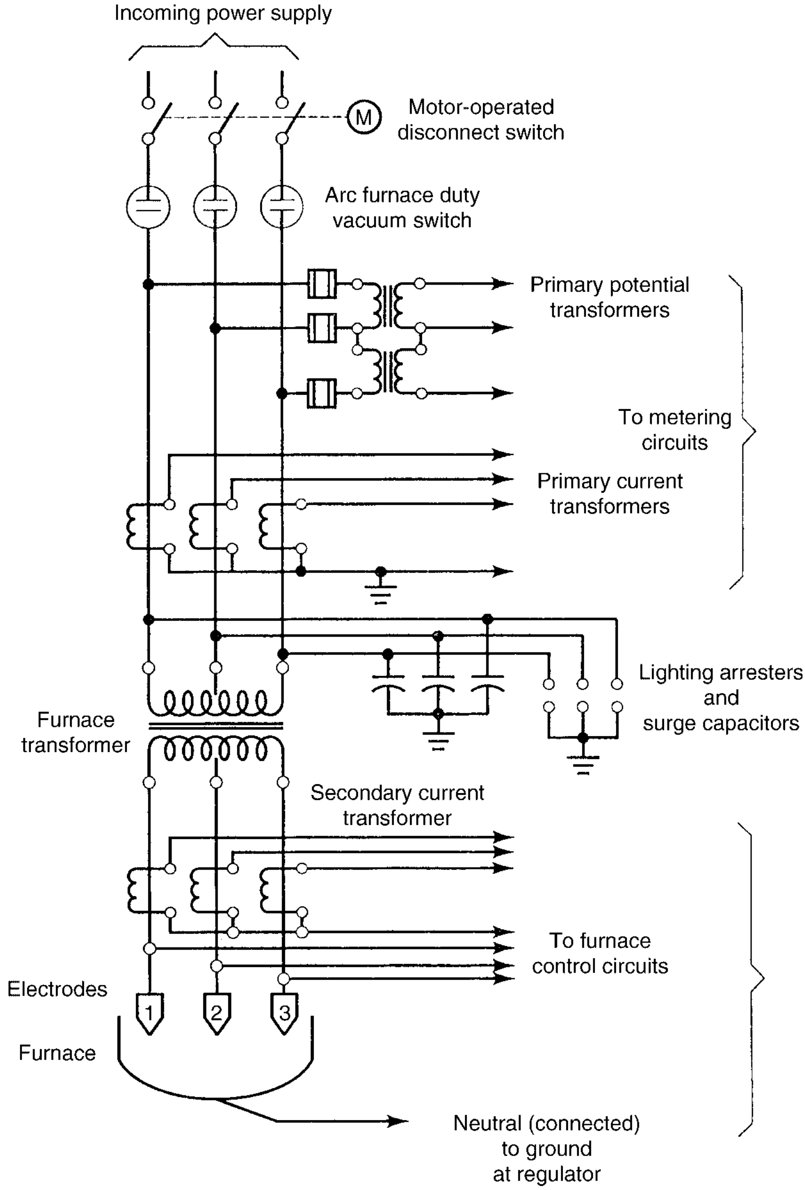

Fig. 10. Three-phase direct-arc furnace schematic.

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 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 (5). 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. Recently furnaces are being designed for eccentric bottom tapping (EBT) as shown in Figure 9. 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.

Refractory Linings. The refractory linings (6,7) 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 (8).

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 (9,10) are popular and are used to replace up to 95% of the wall and roof refractories above the sill or slag line for EBT furnacesand 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 (11) 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. In the early 1990s, inert gas stirring through porous refractories or tuyeres in the hearth is being practiced. Energy and alloy savings were claimed as well as increased yields due to improved slag/metal mixing.

Electrodes. Almost all the electrodes (12,13) 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.

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 (14). 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 (15). Typical operating power factors range from 0.68 to 0.82.

Vacuum-Arc Furnace. Another type of open-arc furnace is the vacuum-arc furnace (16) which is used for melting metals that have high temperature melting points, eg, titanium, molybdenum, and tungsten, or for upgrading alloy steels (Fig. 11). 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

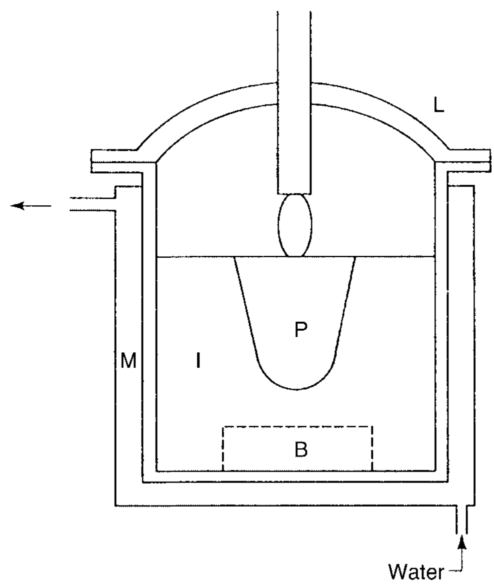

Fig. 11. Consumable-electrode melting in the vacuum-arc furnace (17). A, arc; B, button; E, electrode; I, ingot; L, lid; M, water-cooled mold; and P, pool of molten metal.

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.

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 (18) or more (19) 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.

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 (20) 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.

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 ofphosphorus,calcium carbide, ferroalloys, silicon, other metals and compounds (21), 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.

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 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.

Electrodes. Because of the numerous different processes, there are many different types of electrodes in use (13), 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 (12–22) 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. 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 12. 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.

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 kW·h/t of product, depending on the materials to be processed and the

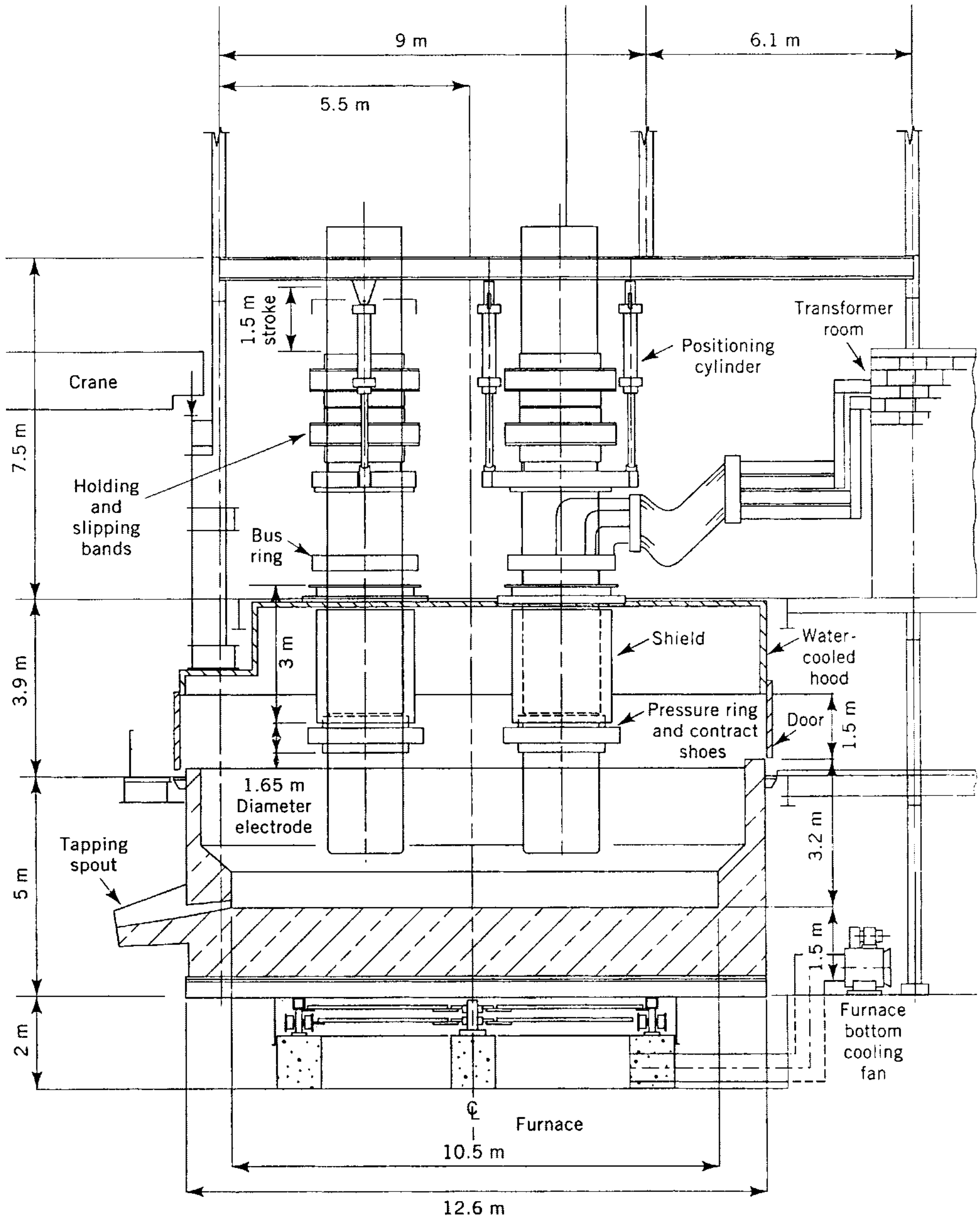

Fig. 12. Design of a ferroalloy furnace. (Courtesy of Lectromelt Corp.)

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 (23–25).

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.

4. Induction Furnaces

Induction furnaces utilize the phenomena of electromagnetic induction to produce an electric current in the load or workpiece. This current is a result of a varying magnetic field created by an alternating current in a coil that typically surrounds the workpiece. Power to heat the load results from the passage of the electric current through the resistance of the load. Physical contact between the electric system and the material to be heated is not essential and is usually avoided. Nonconducting materials cannot be heated directly by induction fields.

Utility power distribution grids normally operate at a fixed frequency of 50 or 60 Hz. These frequencies can be utilized directly for the induction process if the load characteristics are appropriate. If they are not, specific applications can be optimized by the use of variable and higher frequencies produced by solid-state frequency power converters connected between the supply and the load.

The efficiency of an induction furnace installation is determined by the ratio of the load useful power, P_n, to the input power P_o, drawn from the utility. Losses that must be considered include those in the power converter (transformer, capacitors, frequency converter, etc), transmission lines, coil electrical losses, and thermal loss from the furnace. Figure 13 illustrates the relationships for an induction furnace operating at a constant load temperature with variable input power. Thermal losses are constant, coil losses are a constant percentage of the coil input power, and the useful out power varies linearly once the fixed losses are satisfied.

4.1. Induction Heating. *Design.* The coil of an induction heater typically encircles the load, as shown in Figure 14. The current intensity within the load is greatest at the surface and diminishes to zero at the center (Fig. 14**a**) (26). This crowding of the current close to the surface is known as skin effect. The rate at which the current intensity decreases from its maximum value at the surface is a function of the applied frequency, the resistive and magnetic properties of the load, and the load diameter. A useful term in induction design is reference depth, which is defined as the thickness of a shell that with a constant value of current equal to the current at the surface of the load results in developing the same power as the actual load (Fig. 14**b**). The electrical efficiency of an optimized induction heating coil and load combination as a function of reference depth is shown in Figure 15. The curve suggests that a minimum load diameter of four times the reference depth is desirable for reasonable efficiency.

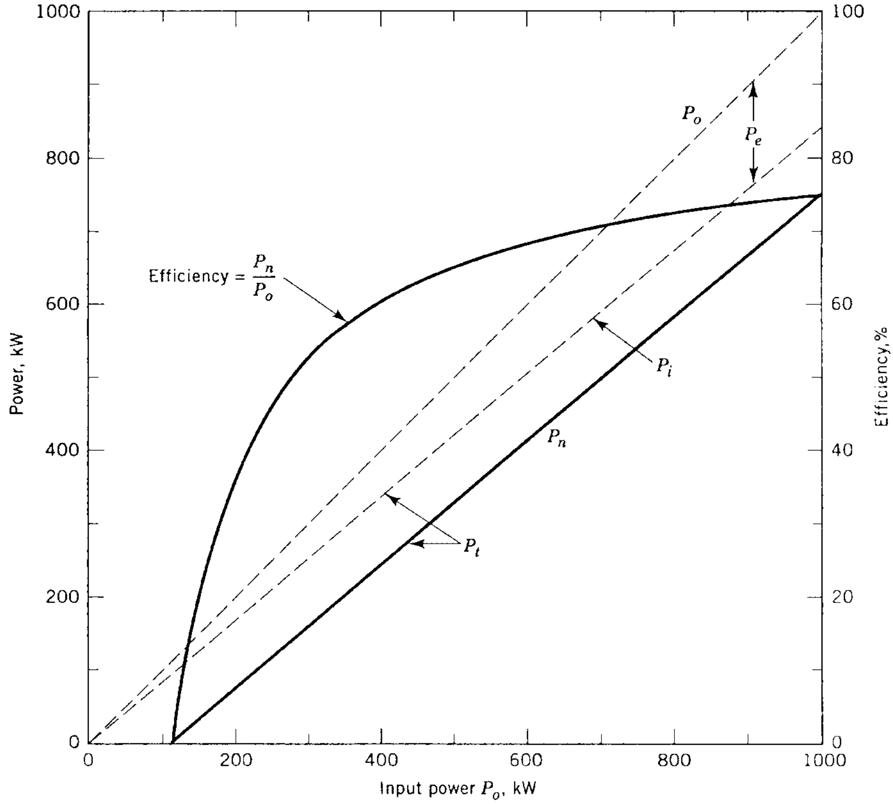

Fig. 13. Induction furnace efficiency. Typical characteristics of a 1000 kW furnace. Example: $P_e = 15\%$ of P_o and $P_t = 100$ kW. P_n = useful power; P_o = power input; P_e = electrical loss; P_i = induced power; and P_t = thermal loss.

Power Supplies and Controls. Induction heating furnace loads rarely can be connected directly to the user's electric power distribution system. If the load is to operate at the supply frequency, a transformer is used to provide the proper load voltage as well as isolation from the supply system. Adjustment of the load voltage can be achieved by means of a tapped transformer or by use of a solid-state switch. The low power factor of an induction load can be corrected by installing a capacitor bank in the primary or secondary circuit.

Some induction heating furnaces must operate at frequencies higher than the supply frequency. Formerly, rotating motor alternator frequency converters were used. Now the availability of high speed, high power silicon controlled rectifiers for use in frequency converters has made rotary converters obsolete. Modern units operate at higher efficiency, cost less, require less factory space, and coordinate readily with process controls (27).

4.2. Induction Melting. Induction melting applications almost always contain the liquid metal charge within a hearth formed by a suitable refractory material. It is possible to design the hearth to satisfy a wide variety of application requirements ranging from a few kilograms to hundreds of tons of metal and

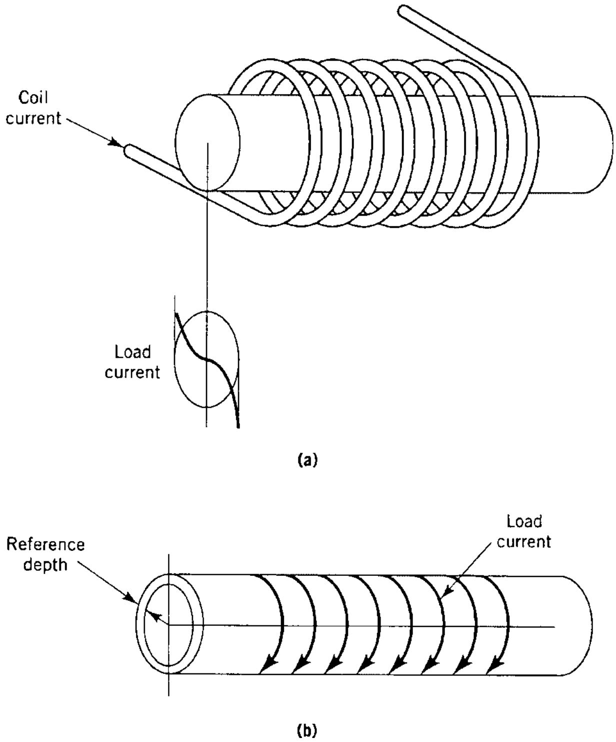

Fig. 14. Induction heating coil and load showing (**a**), current distribution in load, and (**b**), reference depth.

for operation in normal or hostile environments. As the heat is developed within the charge, the metal and the furnace refractory are not exposed to excessive temperatures that may be present in either electric arc or fuel-fired furnaces (28,29). Operation is practical in vacuum or inert atmospheres for the production of critical materials that require protection from oxygen or other gases. The environmental impact of an induction furnace is generally less than that of an equivalent fuel-fired furnace.

4.3. Coreless Induction Furnaces. Coreless furnaces derive their name from the fact that the coil encircles the metal charge but, in contrast to the channel inductor described later, the coil does not encircle a magnetic core. Figure 16 shows a cross section of a typical medium sized furnace. The coil provides support for the refractory that contains the metal being heated and, therefore, it must be designed to accept the mechanical loads as well as the conducted thermal power from the load. In small coreless furnaces the coil itself may possess sufficient strength to allow satisfactory operation. Larger furnaces provide support to the coil from surrounding structures.

Frequency Selection. When establishing the specifications for a coreless induction furnace, the material to be melted, the quantity of metal to be poured for each batch, and the quantity to be produced per hour must be considered

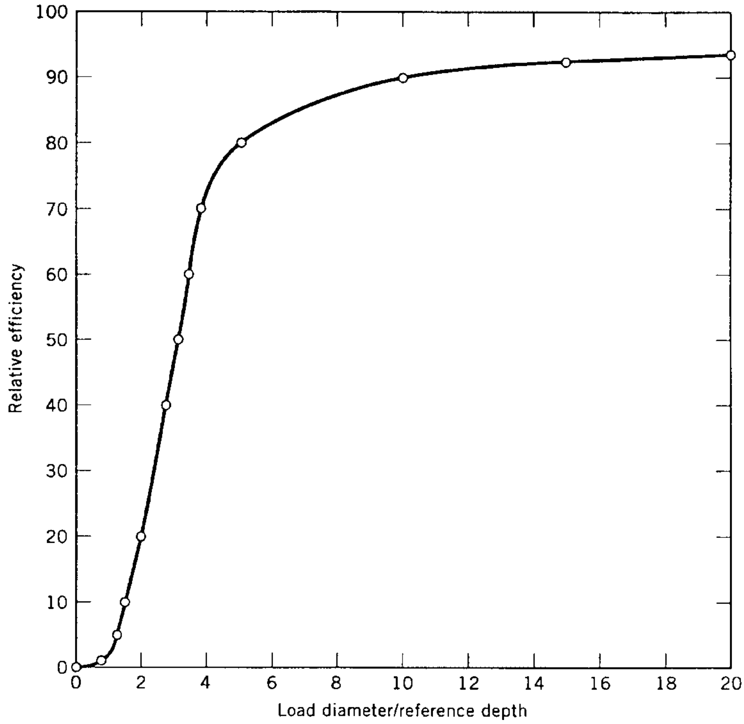

Fig. 15. Relative coil efficiency vs ratio of load diameter to reference depth.

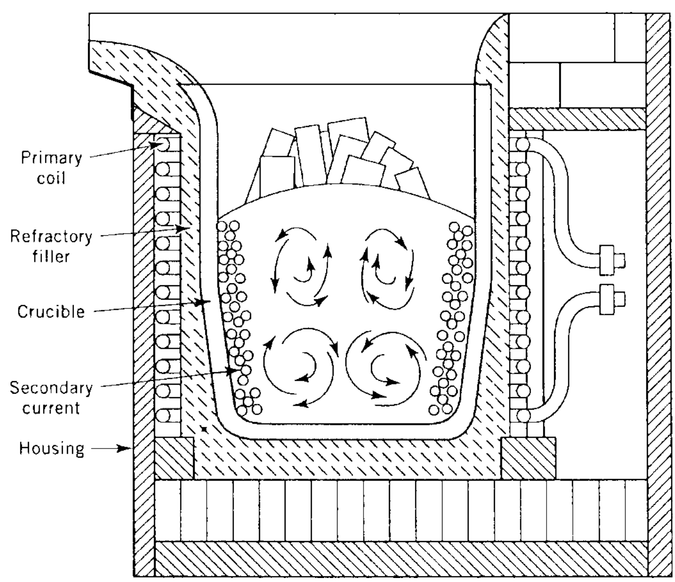

Fig. 16. Small coreless-induction furnace, 500-kg high frequency furnace with insulating board housing and crucible.

simultaneously. Graphs have been developed that combine these factors with practical experience to indicate possible solutions for a specific requirement.

Skin effect is utilized in the design of coreless furnaces. It is particularly evident when the furnace is full of molten metal. Current and power are distributed within the volume of metal just as they are in an induction heating load. In both cases power density at the center of the coil is greater than at the ends of the coil, and in the coreless furnace this results in a circulation of metal. This circulation assists in the melting process by carrying the charge below the surface of the melt and assures a uniform bath temperature and metallurgical homogeneity. The use of lower frequencies produces stronger circulation in the same furnace at the same power level.

Operation. Small and medium sized coreless induction furnaces powered from high frequency power supplies can be started with a charge of metal pieces at room temperature, usually scrap material of appropriate alloy. The charge material is selected to allow a reasonable power to be drawn from the power supply. As the metal charge begins to melt, a molten pool is established and the charge compacts, allowing additional charge to be added. Alloy additions and temperature adjustments complete the melting cycle (30). Higher operating efficiency is achieved if the next cycle is initiated promptly after the charge is poured off so that the stored energy in the hearth refractory is not lost to the coil cooling water. Large coreless furnaces operating at line frequency are often started with a molten initial charge, although it is possible to start with a charge of solid material. Typical operation of these furnaces involves dispensing 20 to 30% of the furnace capacity and immediately recharging dry or preheated material into the bath as power is applied. These furnaces are usually held full during off shifts to maximize refractory life. An alternative is to empty the furnace and maintain the refractory continuously warm with supplemental heat. Furnaces with capacities of 4.5 to 13.6 t with input power ratings of 825 to 1100 kW/t produce liquid iron at a consumption rate of 550 to 600 kW·h/t.

Hearth. The induction melting coil is almost always round and in the form of a right cylinder. It is highly desirable that the refractory lining within the coil be uniform in thickness, so most hearths are cylindrical whether they hold a few kg or 59 t. There are a few instances of a smaller coil being attached to the bottom of a larger hearth, so the hearth could be modified to suit a particular requirement (31). Oval coils have been built and operated satisfactorily, but they are rare.

4.4. Channel Induction Furnaces. The term channel induction furnace is applied to those in which the energy for the process is produced in a channel of molten metal that forms the secondary circuit of an iron core transformer. The primary circuit consists of a copper coil which also encircles the core. This arrangement is quite similar to that used in a utility transformer. Metal is heated within the loop by the passage of electric current and circulates to the hearth above to overcome the thermal losses of the furnace and provide power to melt additional metal as it is added. Figure 17 illustrates the simplest configuration of a single-channel induction melting furnace. Multiple inductors are also used for applications where additional power is required or increased reliability is necessary for continuous operation (32).

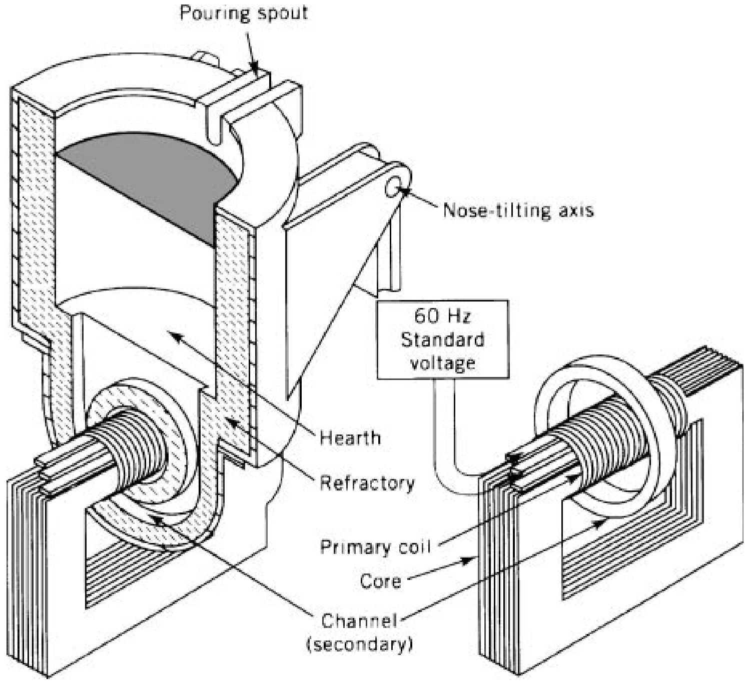

Fig. 17. Basic channel furnace. (Courtesy of Ajax Magnethermic Corp.)

Inductor. The channel inductor assembly consists of a steel box or case that contains the inductor refractory and the inductor core and coil assembly. The channel is formed within the refractory. Inductor power ratings range from 25 kilowatts for low temperature metals to 5000 kilowatts for molten iron. Forced air is used to cool the lower power inductors, and water is generally used to cool inductors rated 500 kilowatts or more.

Metal contained in the channel is subjected to forces that result from the interaction between the electromagnetic field and the electric current in the channel. These inward forces produce a circulation that is generally perpendicular to the length of the channel. It has been found that shaping the channels of a twin coil inductor shown in Figure 18 produces a longitudinal flow within the channel and significantly reduces the temperature difference between the channel and the hearth (33).

Hearth. The hearth of a channel induction furnace must be designed to satisfy restraints that are imposed by the operating inductor, ie, the inductor channels must be full of metal when power is required, and it is also necessary to provide a sufficient level of metal above the channels to overcome the inward electromagnetic pressure on the metal in the channel when power is applied. Once these requirements are satisfied, the hearth can then be tailored to the specific application (34). Sizes range from stationary furnaces holding a few hundred kilograms of aluminum to rotating drum furnaces with a useful capacity of 1500 t of liquid iron.

The refractory used to construct the hearth can be in the form of bricks, preformed shapes, or monolithic. Often a furnace design utilizes all three. Openings

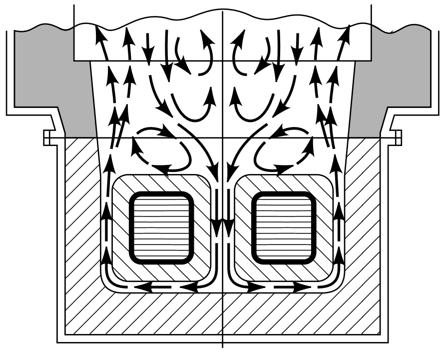

Fig. 18. Twin coil, jet flow inductor. (Courtesy of Ajax Magnethermic Corp.)

or passageways through the walls are fashioned in the same manner as windows in a brick building.

The steel shell that encloses the refractory is exposed to significant forces from the expansion of the refractory as well as the load from the refractory and the charge within the furnace. Similarly, the structures that support the furnace and the foundations must be designed to assure safe operation. A failure of any component can have serious consequences.

Operation. Channel furnaces can be used for melting or holding metal. In either case, the inductor and the hearth refractory are preheated to avoid thermal shock as the liquid metal is introduced at start up. Once the inductor channel has been flooded, it is rarely emptied until the inductor is taken out of service. Inductor life can vary from six months to a number of years depending on the metal alloy and the size and power rating of the inductor. Channel melting furnaces are often designed so that a large portion of their total capacity can be discharged by tilting or rotating the furnace. Dry or preheated metal is added to the furnace at the melt rate of the furnace.

Holding furnaces usually operate with a relatively constant metal level. Included in this category are furnaces that supply metal to various casting processes and large pots that hold metal for continuous coating lines. Multiple inductor furnaces are designed so that individual inductors can be replaced without emptying the remaining inductors.

5. Economic Aspects

Selection of an industrial furnace for a given purpose usually involves deciding between electric and fuel-fired furnaces. The words economy and efficiency when used in the true sense in connection with industrial furnaces refers to the heating cost per unit weight of finished, sellable product. Only electric furnaces are practical above 1700°C, but both types generally are considered for lower temperatures. Electric furnaces frequently have a higher capital (amortization) cost. Generally, there is not a decisive difference in energy cost as long as the cost of electricity is based on its generation from fossil fuels. However, in addition to amortization and energy the following potentially significant furnace operating cost factors should always be examined: (*1*) operating labor cost, (*2*) charge material loss (oxidation and vaporization), (*3*) furnace related raw material cost differences, (*4*) cost of rejects (effect of process control), (*5*) environmental control costs (investment and operation), and (*6*) furnace maintenance costs (including relining and electrodes). Electric furnaces often are selected in preference to fuel-fired furnaces because the former are characterized by a significantly lower total operating cost resulting from savings in the six areas just named. The same total operating cost analysis should be used when making the selection between various electric furnace types suitable for the same job. Also included are the costs of maintaining a safe atmosphere. In some furnaces, fuel cost may be the highest cost, but with so many other considerations, heat energy source is not necessarily the most expensive item in the cost equation (35).

The increasing importance of environmental considerations tends to favor selection of electric furnaces. Fuel-fired furnaces emit large volumes of hot products of combustion that contain objectionable gases and particles, which may include vapors or fumes from certain molten charges. The cost of treating these products of combustion to meet clean air standards can be very high, and will increase as standards are tightened. In electric furnaces (particularly resistance and induction furnaces), air pollution control is required only where pollutants emanate from the charge, but cost is much lower in the absence of a large hot gas volume.

Electric furnaces have a much higher efficiency and therefore release considerably less heat into their surroundings, thereby minimizing the need to cool the work area. Induction furnaces are best in this respect because the charge is heated internally and there are no elements operating above charge temperature. Noise control is also increasingly important. Resistance furnaces are quiet. Coil vibration noise may be a problem in induction furnaces, but can be minimized by coil design. Arc furnaces and fuel-fired furnaces generate noise which may have to be controlled (see INSULATION, ACOUSTIC).

6. Health and Safety Factors

Because intense heat is generated in arc furnaces it is understandable that the arc volatilizes such metals astin, 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.

7. Applications

Electric furnaces are used for annealing, brazing, carburizing, galvanizing, forging, hardening, melting, sintering, enameling, and tempering metals, most notably aluminum, copper, iron and steel, and magnesium alloys. Protection of metals is done in exothermic (lean and rich), prepared nitrogen (lean and rich), endothermic (lean and rich), charcoal, exothermic–endothermic (lean and rich), dissociated ammonia, and combusted ammonia (lean and rich) atmosphere.

7.1. Arc Furnaces. 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.

7.2. Induction Furnaces. A unique capability of induction heating is apparent in its ability to heat the surface of a part to a high temperature while the interior remains at room temperature. Proper selection of material, high frequency, and high power density can produce a thin surface hardness with a heat unaffected core (36). The required hardness depth is selected to satisfy the product requirements. The ability to precisely control the power and length of the induction heating cycle allows it to be integrated into complex work handling equipment.

Induction heating using low frequency and low power density when applied to a stationary or moving bar can produce a uniformly heated part suitable for introduction to a rolling mill (37).

Induction heating is used to heat steel reactor vessels in the chemical process industry (38). The heat produced in the walls is conducted to the material within. Multisectioned coils are used to provide controlled heat input to the process material as it passes through the reactor.

High process temperatures generally not achievable by other means are possible when induction heating of a graphite susceptor is combined with the use of low conductivity high temperature insulation such as flake carbon interposed between the coil and the susceptor. Temperatures of 3000°C are routine for both batch or continuous production. Processes include purification, graphitization, chemical vapor deposition, or carbon vapor deposition to produce components for the aircraft and defense industry.

A special coil configuration is used to heat thin strips of metal that cannot be heated efficiently with a coil that encircles the load, as the strip thickness is small compared to the depth of penetration. The transverse flux induction coil is positioned on either side of a strip to produce a uniformly heated strip with good efficiency in a much smaller space than conventional radiant or convective strip heating furnaces (39).

Small and medium sized foundries producing castings for automotive and other similar applications often utilize iron melting channel melting furnaces. They allow melting off shift at lower power demands and make their total working batch available at the start of the pouring shift. Power consumption under these operation conditions ranges from 600 to 880 kW·h/t. More continuous operation can reduce this figure. Furnaces have been designed to superheat liquid iron delivered in 90 t batches prior to its introduction into a basic oxygen furnace (BOF) for conversion to steel. Similar furnaces are utilized for duplexing in conjunction with cupolas in large foundries.

A typical melter installed in a medium sized brass foundry contains 4500 kg of brass and its inductor is rated 500 kilowatts. Brass is an alloy containing copper and zinc. Zinc vaporizes at temperatures well below the melting temperature of the alloy. The channel inductor furnace's low bath temperature and relatively cool melt surface result in low metal loss and reduced environmental concerns. Large drum furnaces have found use in brass and copper continuous casting installations.

A combination of a channel induction holding furnace with an induction heating coil used in a process is called continuous galvanizing. Steel strip is introduced into a zinc bath in a coating pot. In this installation further heating of the strip extends the alloying of iron and zinc to produce a "galvannealed" strip for automobile bodies with improved fabrication and corrosion resistance characteristics(40,41). The control provided by the use of induction furnaces results in a superior product compared to fuel-fired alternatives.

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