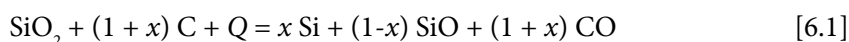


Electric operation

Gudrun Sævarsdóttir

Metallurgical grade silicon and high silicon alloys are produced in Submerged Arc Furnaces (SAF), such as depicted in Figure 6.1. Here, electric current is passed through the raw material mix at various stages of conversion and releases the necessary heat to drive reactions by resistive heat dissipation. The overall reaction of the silicon process can be written as



where Q is the heat that must be added to the strongly heat-consuming reaction. Equation 6.1 is an overall reaction that combines sub-reactions occurring at different locations in the furnace and at different temperatures. Since heat for the reactions in the furnace is released by resistive heat dissipation as electric current passes through the furnace, it is important that sufficient energy is released in the regions of the furnace where the reactions can occur. For example, the metal-producing reaction, which combines the reversed SiO condensation reaction [2.5] and the metal-producing reaction [2.7], requires temperatures above 1800°C to go to the right, at $P_{\text{tot}} = 1$ bar, and close to 2000°C for good silicon yield, as explained in Chapter 2. This high temperature is achieved and sustained by dissipation of electric energy in the furnace. This chapter describes some of the technical aspects of the systems supplying electric energy to the furnace, the conversion of electric energy to heat, the role and properties of electric arcs, and how heat production in the furnace can be controlled.

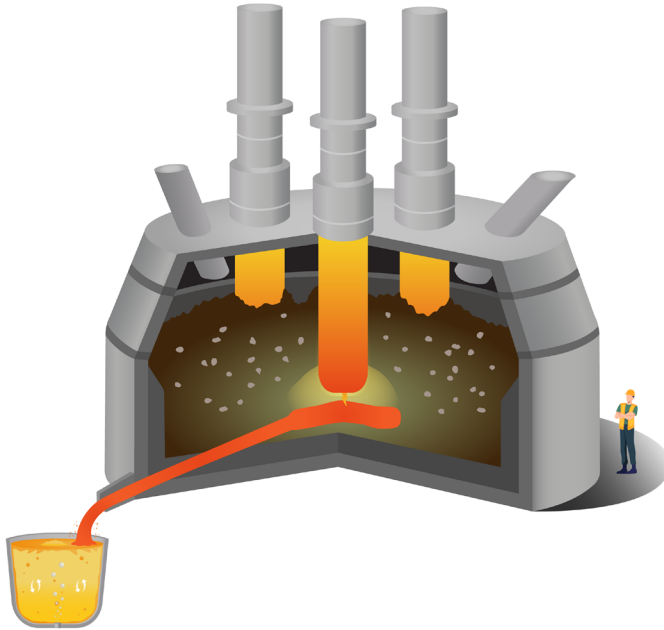


Figure 6.1 *A schematic drawing of a Submerged Arc Furnace.*

6.1 The distribution of heat generation in the furnace

A metallurgist seeking to maintain a well-operated furnace with a high Si-yield needs to pay attention to the selection and feeding of raw materials, ensure proper stoking and mixing, and tapping of the product. In addition, attention must be paid to the electric operation of the furnace, including selecting an appropriate set-point and control strategy for the raw-material mix in the furnace. Electric energy is fed into the furnace through the three electrodes, and a key aspect of the electric operation is to manage where in the furnace the heat is dissipated, and how much is released in the electric arcs as opposed to through Ohmic resistance in the charge.

Heat production

The basic law for resistive heating P as current I passes through a resistance R is:

$$P = I^2 \cdot R \quad [6.2]$$

The main function of the Submerged Arc Furnace is to supply heat for the endothermic reactions contributing to the production of silicon, at the required temperature. Here, R is the combination of the resistances of the materials in the furnace and the arc resistances.

Most silicon furnaces are run with three-phase alternating current, and hereafter U and I refer to the RMS values of voltage and current. If the system is symmetric, the metal bath at the bottom represents the electrical zero point in the three-phase system. The electrode current I passes through a resistance R to the zero point, and real power $P = I^2 \cdot R$ is dissipated as heat. The furnace reactance, and the associated phase displacement φ between instantaneous current and voltage, leads to a relationship $P = U \cdot I \cos \varphi$ between current, voltage, and the real load. This is further discussed in section 6.3. Here the furnace is modelled as a system in which the current passing directly between the electrodes is negligible.

The resistance R is as a rule called the *furnace resistance* or *phase resistance* and can vary slightly between the three electrodes, depending on the conditions around and below each electrode. In the ideal case of a symmetric load, the heat production is the same for all electrodes, and the total furnace heat production P from equation 6.2 becomes:

$$P = 3 I^2 R = 3UI \cos \varphi \quad [6.3]$$

In the following discussion we will assume symmetrical load, even if furnaces are often run unsymmetrically. For unsymmetrical furnaces, the electrodes must be discussed separately.

As a rule, it is important to use the full production capacity, and the furnace will, as far as possible, be run at the fixed optimum load. An infinite number of combinations of voltage and current can give this load, but not all combinations are equally advantageous for the process. Several ideas have been used to establish the strategy for the electric operation of the furnace.

The heat distribution

According to the traditional understanding of the inner structure of the silicon furnace, we can hypothesize that the current is split into parallel branches: one through the arc and one through the charge. Although recent findings indicate a third type of path, through short arc discharges towards more conducting materials, we will combine that path with the charge current pathway in the following analysis. The current distribution is shown in an equivalent diagram for a single-phase furnace with bottom contact in Figure 6.2. This figure can also be interpreted as an illustration of one of the three phases in the furnace. Any current component passing between electrodes further up can be lumped in with the charge current.

It is not necessary, in this discussion, to separate a third type of likely current path: a short arc connecting the electrode and a conducting charge. However, it will be addressed later in the chapter.

As proposed by Westly, the current passing through the charge heats it up (Westly, 1974). This resistive heating, together with heat transfer from the crater zone (partly accomplished through SiO condensation and exothermic SiC formation), will melt silica (SiO_2) as it moves down in the furnace. In the crater zone, which is heated by electric arcs, the SiO_2 is consumed by the crater reaction. This reaction is strongly heat-consuming and requires a temperature of 1980°C to enable maximum yield. If the heat supply to the crater is insufficient, the reaction will not be complete, and molten SiO_2 will accumulate at the bottom. As molten SiO_2 is an oxide melt, it is called slag in other reduction processes. However, one should always remember that the slag in the silicon process is not a waste, but a valuable material that potentially can be utilized by improved operation (except for small amounts of Al_2O_3 and CaO). Westly continued his argumentation with a discussion of the conditions for complete consumption of the molten SiO_2 .

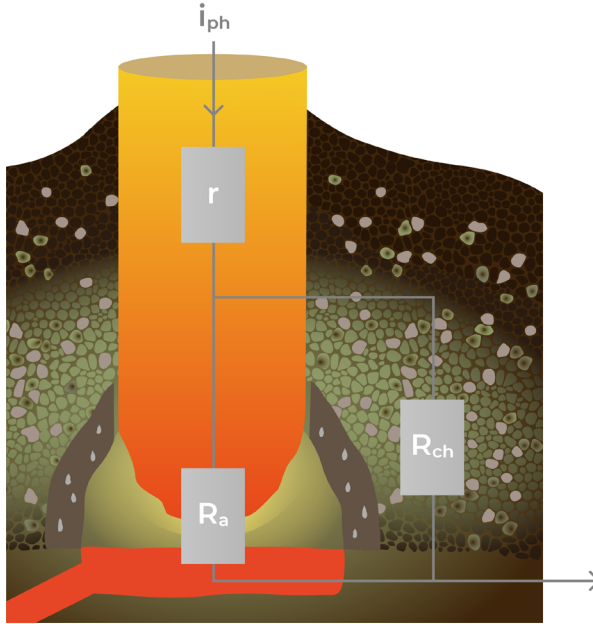


Figure 6.2 Simplified equivalent diagram for the arc and charge resistance in a single-phase furnace.

Westly defined a heat distribution coefficient, C :

$$C = \frac{Q_{ch}}{Q} = \frac{U^2 / R_{ch}}{U^2 / R} = \frac{R}{R_{ch}} \quad [6.4]$$

where

- U is the voltage electrode – bottom
- Q_{ch} is heat produced in the charge
- Q is total heat produced
- R_{ch} is the resistance of the charge
- R is total resistance

The value of the coefficient C varies in the range $0 \leq C \leq 1$. The resistance of the charge varies fairly slowly during operation, while the resistance of the arc can vary rapidly. Its value will be influenced by the choice of electrode position. A too high value, with insufficient arc activity, gives typical symptoms:

- Large production of molten SiO_2 with some SiC
- The load varies only slightly, or only for a short time, when the electrode is raised or lowered
- The electrode consumption becomes low at the tip, but high further up on the side of the electrode, resulting in narrow electrodes.

According to the reasoning above, these symptoms will appear when the heat production in the charge melts more SiO_2 than the crater can consume. The coefficient C has then exceeded a maximum value, $C_{\max}$, at which SiO_2 melting and crater consumption are balanced. The largest acceptable total resistance is therefore, for a given furnace, the charge resistance R_{Ch} .

If a furnace is operated at $R_{\max}$ and the arc resistance is increased while maintaining a constant charge resistance, the overall resistance of the furnace increases and the voltage must be raised to keep the load. The increased voltage will increase the charge current and therefore the heat release in the charge. Since the load is kept constant, the heat production in the arc will decrease. The increase in arc resistance has raised the ratio Q_{Ch}/Q above the acceptable value. It is therefore impossible to increase the total resistance unless the resistance of the charge is also increased.

The heat distribution theory states that a silicon furnace with a certain charge has a maximum resistance that is compatible with good operation. This maximum value is normally not known. The metallurgist selects an operating resistance and corrects it if the symptoms of too high resistance appear. For a chosen load, the current will be lower the higher the resistance. Since the heat losses in the conductors increase with increasing current, as do the stresses on the electrodes, the furnace metallurgist will operate with a resistance that is as high as possible. Therefore, $R_{\max}$ can be seen as an optimum resistance.

Andreae's rule

Andreae gave the first formulation of a relationship between electric operation and furnace behavior around 1930 (Andreae, 1933). He studied the available information from operating furnaces and found that furnaces with good operation results fulfilled a relation

$$\pi D R = k \quad [6.5]$$

where D is the electrode diameter, R is the resistance of one electrode, and k is a constant for a given charge. The factor π was added because the electrode resistance was originally related to the electrode circumference, and k was often called the periphery resistance. The Andreae rule states that the optimum resistance depends on the electrode diameter but is independent of the load. The constant k has a value in the range 0.0030–0.0045 Ωm for silicon.

A simple derivation offers a physical interpretation of the k factor. If we consider the conducting part of the furnace as a cylindrical continuation of the electrode, and we insert the corresponding expression for R (with electric resistivity ρ and l as the length of the contact cylinder), Equation [6.5] changes to

$$k = \pi D R = \pi D \frac{\rho l}{\pi D^2 / 4} = 4 \frac{l}{D} \rho \quad [6.6]$$

If the ratio l/D is constant, k is proportional to ρ , this statement can be expressed more generally: k is proportional to ρ if the conducting elements in the furnaces have the same proportions and differ only in size. Therefore, k expresses the specific resistivity of the charge. This charge resistivity should be interpreted as the resistivity of a certain volume within the furnace, which is difficult to reproduce for accurate measurement in a resistivity cell. In addition, if a significant part of the current passes through an arc, one should be cautious with models that assume conduction through regular geometric forms. However, Andreae's rule can also be useful for the silicon production process.

Westly's rule

Westly carried out a statistical analysis of almost one hundred silicon and ferrosilicon furnaces to establish the connection between load and current (Westly, 1979). He proposed a model to fit the data:

$$\ln I = A + B \cdot \ln P \quad [6.7]$$

and fitted the constants to obtain an empirical relation for the furnaces:

FeSi 75: $\ln I = 2.453 + 0.641 \ln P$ 68 furnaces Correlation coefficient 0.986

Si metal: $\ln I = 2.381 + 0.660 \ln P$ 27 furnaces Correlation coefficient 0.974

Corresponding calculations for furnaces producing other commodities (calcium carbide, ferromanganese, silicomanganese, ferrochromium, silicochromium) gave B values in the range 0.655 to 0.731. Westly concluded that the variation in the B values was random and set it equal to $2/3$. The relation between current and load is thus given by:

$$I = C_3 \cdot P^{2/3} \quad [6.8]$$

where C_3 is a constant that varies to some extent because of the nature of the raw materials and the mode of operation. Westly calculated a mean value 10.662 for silicon metal and 10.865 for FeSi75 for the furnaces he had statistics from (with the units MW for P and kA for I).

The subscript 3 in the constant C_3 indicates that Equation [6.8] applies to a three-phase furnace, with P as the total load and I as the representative phase current. If the load for each electrode is used, individual constants C_1 can be calculated for the electrodes. The Westly rule has the same form whether it is given for one or three electrodes. In calculations, one must remember that P means the whole-furnace load in the C_3 formula, but only the load for one electrode in the C_1 formula. Therefore, the constants C_1 and C_3 are different.

$$I = C_1 \left(\frac{P}{3} \right)^{2/3} = C_3 P^{2/3} \quad [6.9]$$

$$\frac{C_1}{C_3} = 3^{2/3} = 2.08 \quad [6.10]$$

As in the equations above, I is the phase current in one electrode, and P is the overall load of the furnace. Equation [6.10] is useful when comparing the electric operation of single- and three-electrode furnaces.

Westly also considered furnace operation with unreliable power availability. This involves operating the furnace at strongly reduced load for long periods (Westly, 1976; Westly, 1974). According to the Andreae rule, the resistance should then be constant, but Westly found that he had to change the resistance set point to achieve the best operation. However, when he made the value of the k factor dependent on the current density, the rule was still valid. The corrected k was determined as

$$k^2 i = k_1 \quad [6.11]$$

where i is the current density in the electrode and k_1 is a new constant. Combined with the Andreae rule, this equation gives Equation [6.8], which is therefore useful both for dimensioning new furnaces and for changing the load on established furnaces.

The optimal electrical operation of a furnace must be determined during operation for each furnace and charge, but the experience embodied in the Westly rule provides a good estimate of a starting value. If, for some reason, it is necessary to run with a load lower than normal, the rule indicates how the load must be reduced to sustain optimum operation. Equation [6.8] can take several equivalent forms, and the most convenient form depends on the situation. The form in [6.8] is useful when a furnace is controlled for constant current, since it immediately gives the current setpoint when the load is known. If the furnace is controlled for resistance, an equivalent expression can be derived by combining Equation [6.8] with the equation for furnace load [6.3] which gives the following relationship:

$$P = 3I^2 R = 3 C_3^2 P^{4/3} R \Rightarrow P^{1/3} R = C_X \quad [6.12]$$

The expressions for C_3 and C_X are not dimensionless, therefore, their numerical values vary with the choice of units. For C_3 , the chosen units are normally kA and MW, giving C_3 a value of around 10. If we use the units MW and mΩ, C_X will be around 3. With this choice of units, the relationship between C_3 and C_X is:

$$C_x = \frac{1}{C_3^2} \cdot \frac{1000}{3} \quad [6.13]$$

The Westly rule is an empirical rule based on experience with varying loads on the same furnace and on a statistical investigation of a large number of industrial furnaces. Its foundation is essentially the condensed experience of many metallurgists around the world. They tried to optimize operation by trial and error, and furnaces of many different sizes ultimately settled into a state described fairly accurately by the Westly rule. Thus, it seems safe to use it as an empirical rule, even though it lacks a theoretical foundation. It is equivalent to Andreae's rule for constant current density in the electrode, and it shows how Andreae's parameter k varies with the current density.

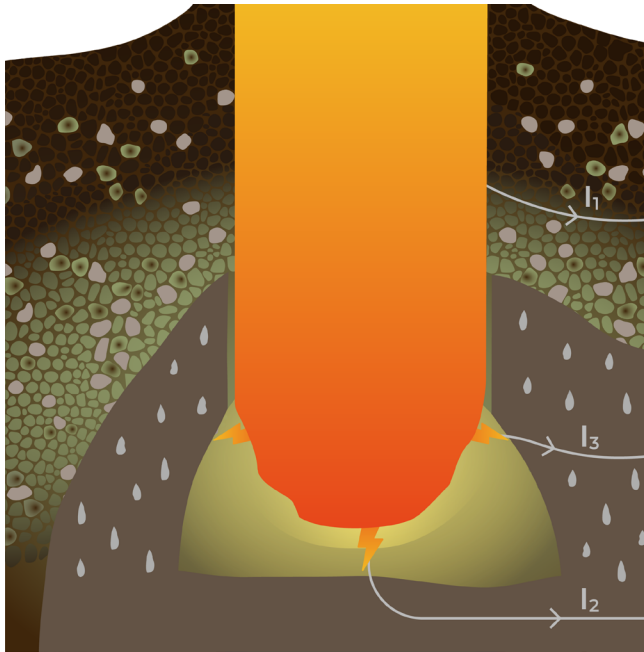


Figure 6.3 A schematic of alternative current paths from the electrode through the furnace. The current paths correspond to the description in the text.

6.2 Current paths

Furnace excavations have revealed large variability in the inner structure of furnaces. A schematic of one version of the current-conducting inner structure of the furnace is shown in Figure 6.3. Normally, the lower part of the electrode is surrounded by a cavity. The upper part of the cavity walls consists of a partly transformed charge of SiO_2 , C, SiC and condensate with rather low conductivity. In some cases, it is partly converted to and mixed with Si, and is thus more conductive. The lower part mainly consists of reaction products, Si and SiC, mixed with molten silica, and has fairly high conductivity.

The material layers are volume conductors with a very large cross section, so the current is a distributed volume current. The figure indicates that there are principally three current paths from the electrode:

1. Electrode – charge – furnace interior
Ohmic conduction through a bed of charge particles, denoted I_1 in Figure 6.3.
2. Electrode – gas space – high conductivity metal penetrated bottom – furnace interior
Plasma arc in the gas-filled cavity towards metallic conduction, denoted I_2 .
3. Electrode – narrow gas-filled gap to partly converted charge materials to furnace interior
Combination of all conduction mechanisms listed above, denoted I_3 .

Current passing from one electrode to the others is sometimes represented as a fourth current path, but it can be seen as a variant of the first one.

The current path from the furnace interior to the other electrodes is through any combination of the same mechanisms.

Distribution between paths

The distribution of the current between these paths is hard to measure, and the concept is mainly built upon indications and speculations. Estimates – based on methods such as estimating the slope of the Lissajous curve for the real voltage and current, as indicated in Figure 6.12.b – suggest that around

30–60% of the phase current passes without arcing, directly through charge materials (Haraldsson *et al.*, 2023; Sævarsdottir and Bakken, 2010).

The electric arc (or, more likely, arcs) is important for metal production, as arc temperatures above 10,000 K form a heat source that can supply heat to reactions that require very high temperatures to proceed in the right direction. In this lowest part of the furnace, the reactants SiO_2 and SiC are present. Along with the liquid Si and the gaseous products SiO and CO , they need a reaction temperature of around 1980°C to reach an equilibrium with equal partial pressures of SiO and CO , which enables a good Si yield (See eq. 2.7). There is likely more than one arc on each electrode. They are not in fixed positions, but move erratically around near the tip of the electrode or along the sides.

The resistance of the furnace is regulated by raising and lowering the electrode tip. When it is lifted above a certain position, the distance to conducting material at the side of the crater will be shorter than the distance to the bottom. Since the arcs will always try to find the path of lowest resistance, most of the current will go to path I_1 and I_3 at the upper part of the conducting hot furnace zone. If the sides of the cavity are steep, the resistance will then vary only slightly with the electrode position. The electrode will be consumed by the arc away from the tip, and it will develop an irregular form, but may remain long and narrow. The charge materials sink to the bottom of the cavity and, because of the distance from the arc, they receive a relatively low fraction of the heat. The result is that unreduced SiO_2 , with some SiC , is collected at the bottom and is characterized by slag and problematic tapping. This state is what is normally interpreted as symptoms of the current path being too high in the furnace, or a ‘short current path’, which can be caused by a furnace resistance being above the allowed maximum (as previously discussed). A ‘short current path’ can be detected by a reduction in the furnace reactance, as displayed in the furnace control system, which increases the power factor $\cos(\varphi)$. This phenomenon is reported in (Tsfahunegn *et al.*, 2021).

The excess of the SiO_2 -containing charge at the bottom has low conductivity, and it may make it difficult to re-establish the bottom arc even when the resistance is lowered. However, the largest resistance in the current path is still an arc, not a charge current. In a stationary furnace, the electrode will be in the centre of a hole into the high-conducting layer, and the arc may burn in any position around the electrode. In a rotating furnace, the electrode will be in a circular trench, and there are predominantly two directions – inwards

and outwards – that are open for the arc to the side. Upstream, the material will get closer to the electrode and arc, and electrode consumption will tend to be higher on that side. If a furnace is run for a long time on high resistance, the control system will place the electrode at the top of the high-conducting layer. If the two sides of the trench are not equally high, the electrode tip will be consumed preferentially on one side and develop a slanting tip.

A charge current I_c passes a resistance that does not change significantly when the electrode is moved, except that the contact points connecting charge and electrode may be disrupted by the movement. The current through this path is not readily available for measurement, but the effect of the heating can give indications of its magnitude. The energy needed to heat the reactants to the reaction temperature is small compared with the heat of reaction. It has been argued that if a large fraction of the current flows along this path, the heat will melt the SiO_2 , and the roof of the cavity will soon break down. Therefore, it can be concluded that the resistance along this path is much larger than the arc resistance, and that during normal operation only a relatively small fraction of the current flows through it. However, estimates from Lissajous curves with the reactance removed, as discussed above and shown in Figure 6.10.b, indicate a significant charge current component. If a furnace is operated at a resistance that is somewhat too high, the charge current will increase to some extent, but not enough to make the current insensitive to the electrode position.

The Westly rule is an empirical rule based on extensive practical experience. Westly showed that it could be derived theoretically by an extension of a study by Bøckman, where it is shown by dimensional analysis that (Bøckman, 1960; Westly, 1976)

$$\frac{R \cdot D}{\rho} = \text{constant} \quad [6.14]$$

Here is the resistivity of the conducting space in the furnace, and D is a linear dimension. Bøckman's analysis assumes that furnaces of different sizes can be geometrically and electrically similar. Two furnaces are geometrically similar if all linear dimensions are scaled by the same factor. Linear dimensions include, for example, electrode diameter, electrode spacing, crucible diameter, and crucible depth. The furnaces are electrically similar if the current density

is the same at all corresponding points. When these similarity requirements are fulfilled, Equation [6.14] gives Andreae's rule.

We insert

$$R = \frac{P/3}{I^2} \text{ and } I = c_b D^2$$

into Andreae's rule, with constants c_b and c_c , and obtain

$$\pi R D = \pi \frac{P/3}{I^2} \sqrt{\frac{I}{c_b}} = c_c \frac{P/3}{I^{3/2}} = \text{constant}$$

$$\Rightarrow I = C_3 P^{3/2} \quad [6.8]$$

Which is, again, Westly's rule, Equation [6.8].

However, there are difficulties with the assumptions behind this deduction. Bøckman's Equation [6.14] gives Andreae's rule only if the conductivity of the conducting volumes is the same at corresponding points in furnaces of various sizes. However, conductivity varies with temperature, which is in turn determined by the balance between heat production and heat loss.

Heat production is proportional to volume, while heat flow out of the volume depends on the product of surface area and temperature gradient. Most of the energy should be consumed by the heat-consuming reactions within the volume considered. As for heat loss, a larger furnace should lose proportionally less heat by conduction if the gradient is similar. However, significant heat and chemical energy are carried from the crater zone with the gases. So far, the argument has applied to a solid conductor. If the conductor is a fluid, as the plasma arc is, convection will contribute to heat transport and make the situation more complex. Therefore, it is not self-evident that the conducting volumes in two furnaces of different size will be electrically similar, which is a weakness in the assumptions on which the Westly equation is based. The simplifications made still enable a qualitative understanding of the important fundamentals.

In principle, the current distribution through the furnace can be calculated if the resistivity of the furnace content and its temperature dependence are known. Heiss set up a model of the electric smelting furnace based on

Maxwell's electromagnetic equations coupled with the temperature field (Heiss, 1982). However, the model produced rather complicated non-linear partial differential equations, and he had to apply strong simplifications. In recent years, Tesfahunegn and Herland have modelled the current distribution in Submerged Arc Furnaces for silicon and FeSi production. However, even with advances in computational power and access to sophisticated software platforms, the models require many simplifying assumptions to run (Herland *et al.*, 2019; Tesfahunegn *et al.*, 2021). Thus, different models yield different findings, depending on the simplifications made. Another difficulty is the continuing lack of reliable physical properties for the materials at the various reaction stages in the furnace, even though significant efforts have been made to measure these properties at elevated temperatures, as shown later in this chapter. Modelling the current distribution using the measured properties overestimates the furnace resistance. To obtain more realistic estimates, it would be necessary to measure at temperatures approaching 2000°C and to include the effects of molten slags. The effect of slags is even more important in FeSi furnaces, as iron oxide is reduced to metal by CO and increases the conductivity of both the charge and molten SiO₂ mixes.

Larsen *et al.* have simulated the alternating current electric arc in the silicon furnace, using data for SiO–CO gas compositions (Haraldsson *et al.*, 2024; Larsen, 1996; Sævarsdóttir, 2002). Nonetheless, much theoretical and experimental work remains to be done on the current through the charge and the gas cavity in order to obtain a full understanding. The empirical Westly rule is, therefore, still important and useful guidance for the practical metallurgist.

The Westly rule gives the optimum furnace resistance for a given load, based on empirical data. Heat distribution theory provides a physical interpretation, but it can only state that there is a maximum allowable furnace resistance. In the terminology of the Westly rule, it states that there is a minimum allowable value of C_3 . The maximum allowable resistance can also be given an alternative interpretation. The furnace operator controls the resistance by raising or lowering the electrode, which means that a high resistance corresponds to longer, fewer arcs, or to a larger part of the current being forced through the resistive charge. This leads to more heating in the upper parts of the furnace and less in the lower part, where the metal is produced and tapped.

Sometimes the current through the furnace is analysed using a detailed equivalent circuit. An example is shown in Figure 6.4 (Sævarsdóttir, 2002).

In addition to the current paths shown, some current is conducted directly between the electrodes through the charge, but these paths are likely small. Moreover, when setting up an equivalent circuit, it is not possible to separate the resistive current paths higher up in the furnace from other ohmic parallel resistance.

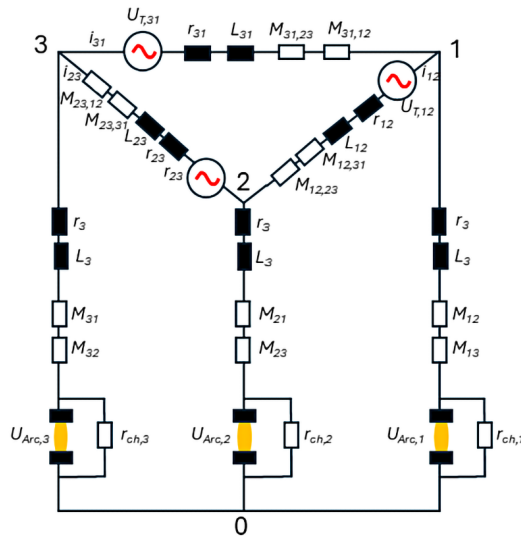


Figure 6.4 Equivalent circuit for a three-phase submerged arc furnace. The figure shows the furnace part of a circuit with electrodes in Knapsack connection. [With permission from Sævarsdóttir (2002)].

Notation: I current, U voltage, L inductance and M mutual inductance; 1, 2, 3 the phase or electrode numbers.

Current through the charge

In this chapter we will explore the properties of the charge vs. the properties of the electric arcs.

How energy is dissipated in the furnace depends on the current paths within the furnace, which are determined by the electrical conductivities of the materials filling it. In the case of Si production, the charge materials fed into the furnace are a combination of quartz, coal, coke, charcoal and wood chips; in the case of ferrosilicon production, iron oxides are added. A number

of researchers have studied the physical properties of these charge materials, most importantly electrical conductivity. Krokstad measured the resistivity of several grades of industrial SiC crusts (Krokstad, 2014). These data, along with a summary of some available material property data as a function of temperature, are shown in Figure 6.5 (Eidem *et al.*, 2010). Hoover measured the resistivities of a range of compounds, as summarised in Figure 6.5 (Hoover, 2023; Hoover *et al.*, 2023, 2022). They also studied mixtures of charge materials, including quartz and iron oxide, with results for 1400°C as shown in Figure 6.6.

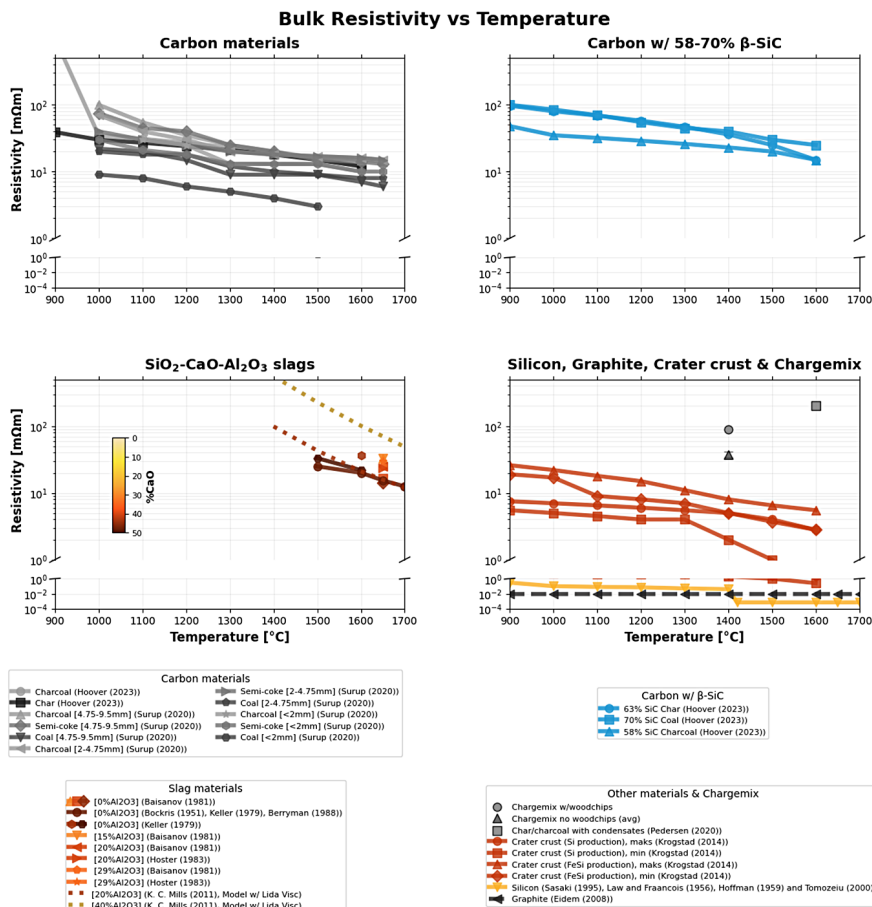


Figure 6.5 The material resistivity of materials used in the silicon furnace compiled by Sindland (Sindland *et al.*, 2027).

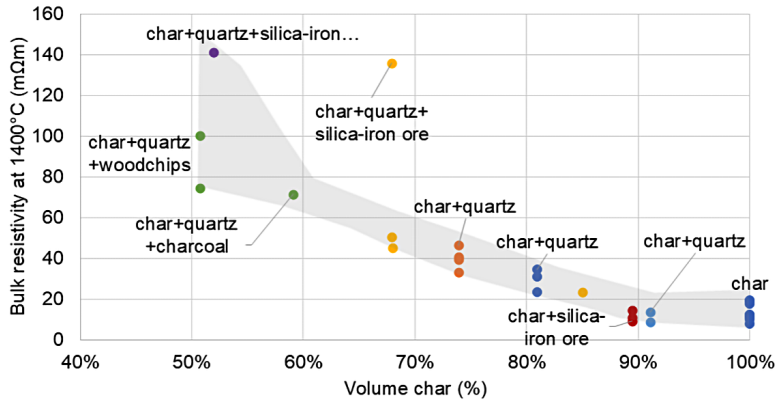


Figure 6.6 Resistivity at 1400°C for all charge mixes as a function of the volume% char. Data points are labelled with their mixtures. [From (Hoover et al., 2023) used under Creative Commons CC BY licence].

In general, the findings show a wide range of resistivities. Quartz is a relative insulator, whereas carbon materials show varying degrees of conductivity, depending on type and temperature. Coke is a relatively good conductor even at low temperature, while charcoal is the most resistive. Wood chips were not tested, but are assumed to be mostly insulating, however, they will turn to charcoal in the furnace. SiC, both intrinsic and from industrial crust, is less conductive than the carbon it is made from, even when Si metal is demonstrated within the SiC crust. However, as temperature rises towards and above 1600°C, the resistivity of all these materials converges towards values below 40 mΩm, and mostly below 20 mΩm. Much of the increase in conductivity in carbon materials occurs as volatiles are driven off, because carbon materials that are heat treated before the experiment have low resistivity even at lower temperatures. For the silica containing charge mixtures at 1400°C, resistivity ranges from 10 to 150 mWm, depending on parameters such as particle sizes, ratios and carbon type.

Older work by Vorob'ev and Mikulinski measured the resistivity of the charge mixture for Si, FeSi90 (ferrosilicon with 90% wtSi %), FeSi75, FeSi45 and FeSi20 (Vorob'ev and Mikulinski, 1969). At low temperatures, the silicon charge had the highest resistivity, and this resistivity dropped with increasing iron content. The iron was added as iron filings, which reduced the resistivity strongly. As temperature increased, however, the resistivity decreased for all charges, and at 1600°C all charges had the same resistivity, about 150 mΩm.

Rennie measured the resistivity of charges for FeSi75 with coke, char or coal as reductants (Rennie, 1975). Charges with coal had a high resistivity up to about 800°C, where the volatiles were driven off. The resistivity then became fairly constant with increasing temperature until 1400–1500°C, where it dropped rapidly. Rennie argued that this resistivity decrease occurred partly because softening of the quartz gave better contact between the particles. Resistivity was measured while the charge was heated to 1700°C over 6 hours. Measurement continued during cooling, and the resistivity remained low, which is consistent with the removal of volatiles improving conductivity.

It should also be emphasised that the type of carbon material influences charge conductivity: the higher the volatile content, the higher the resistivity. The porous structure of charcoal makes it slightly more resistive at high temperature than coal at high temperature, but at lower temperature the difference is much larger, presumably due to the volatile content. This can be seen from the data in Figure 6.7, where resistivities were measured for similar particle sizes. The coal was calcined at 1200°C before the resistivity measurements (Hoover *et al.*, 2023). In addition to Hoover's work, the figure includes data from (Pedersen, 2020).

Measurements also show that SiC has higher resistivity than the carbon it is made from, even when partly impregnated with Si. An example is shown in Figure 6.8. The data show that, in some cases, the SiC resistivity can be comparable to the heat treated coal, although the general rule is that SiC has higher resistivity.

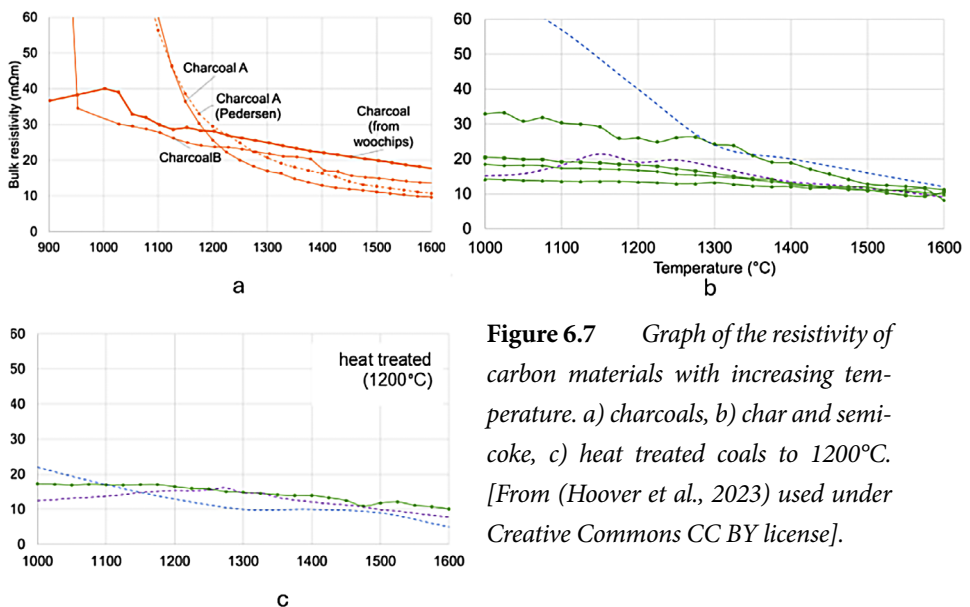


Figure 6.7 Graph of the resistivity of carbon materials with increasing temperature. a) charcoals, b) char and semi-coke, c) heat treated coals to 1200°C. [From (Hoover *et al.*, 2023) used under Creative Commons CC BY license].

The relatively higher resistivity of SiC, compared with the unreacted carbon, partly goes against previous assumptions, for example in the earlier version of this book. For all these compounds, the resistivity decreases with increasing temperature, which reduces the difference between the different mixtures.

In general, it is not trivial to obtain reliable, repeatable measurement results from these systems. In addition to the intrinsic resistivity of the materials in the mix, the results depend on particle size, contact resistance and, more generally, the layout of materials and potential segregation in the case of mixed charges, as this affects the contact points and current paths. What can be said is that, although volatile-rich carbon materials will produce a more resistive furnace charge, the difference in resistivity decreases further down in the furnace as the temperature rises. Loose charge is also more resistive than a crusty charge with a more continuous structure. In general, the resistivity data presented here would give a much too high furnace resistance compared with the industrial furnace, so they should not be used uncritically. One factor is that the data are generally collected at temperatures below 1600°C, which should contribute to too high a resistance value, as the resistivity generally drops as temperature rises in these materials. In addition, the effect of molten slag is not included in the data. It is known that molten silica contributes to lowering the resistance, in particular in FeSi furnaces containing iron raw materials in the charge.

Excavations of furnaces show that the distribution of the different types of materials in the furnace is highly dependent on the operational conditions leading up to the furnace shutdown. A recreated cross section of two furnaces at Bjølvfossen FerroSilicon plant in Norway can be seen in Figure 6.8.

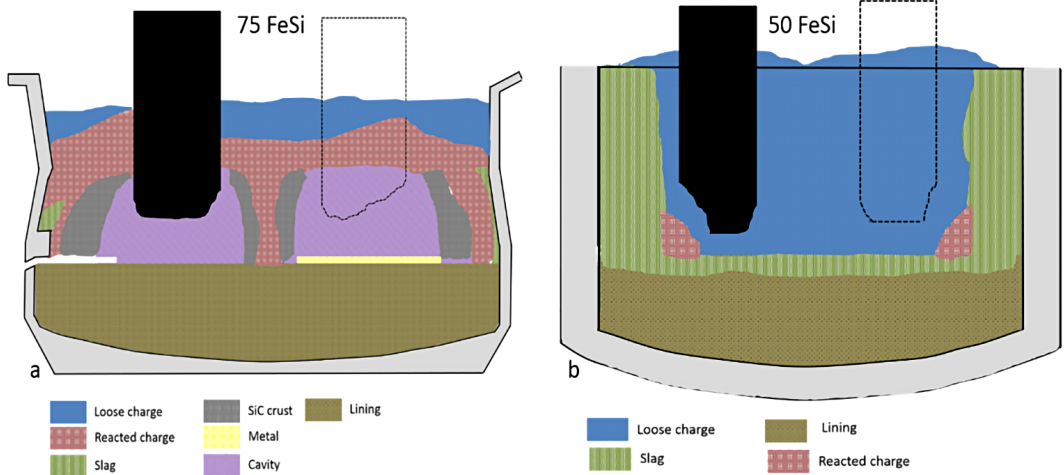


Figure 6.8 Overview of zones in two FeSi furnaces: a) 75 FeSi in Finford, b) 50 FeSi in Elkem Bjølvfosen. [With permission from (Ksiazek et al., 2016)].

Excavations have confirmed the existence of a gas-filled cavity, although its size varies, surrounding the electrode tip. This cavity is present in submerged arc furnaces used to produce high-silicon alloys, but not necessarily in other ferroalloy processes. Some excavations have revealed no cavity; however, it must be kept in mind that excavations are highly disruptive and are normally not carried out on well-operating furnaces. This cavity, also called a crater, is attributed to arcing, as a significant part of the phase current exits the electrode through one or more electric arcs. Arc formation requires a certain voltage drop, as it involves the electrical breakdown of gas molecules to form conductive plasma. The arc is described more thoroughly in the following section.

Table 6.1 *The order of magnitude of the resistivity of materials in the silicon process. (Based on Hoover et al., 2022; Krokstad, 2014; Schäfer, 1984; Valderhaug, 1992).*

Material	Temperature	Resistivity
Quartz	$T < 1800 \text{ K}$ $1800 \text{ K} < T < 2000 \text{ K}$	$\rho > 10^4 \Omega\text{m}$ $10^2 \Omega\text{m} < \rho < 10^4 \Omega\text{m}$
Carbon materials	$T < 1800 \text{ K}$	$500 \text{ m}\Omega\text{m} > \rho > 10 \text{ m}\Omega\text{m}$ $\sim 0.1 \Omega\text{m}$ for Graphite
Silicon carbide	$T \approx 2000 \text{ K}$	$1000 \text{ m}\Omega\text{m} > \rho > 20 \text{ m}\Omega\text{m}$
Silicon	$T \approx 2000 \text{ K}$	$\rho \approx 0.01 \text{ m}\Omega\text{m}$
Plasma	$T > 15000 \text{ K}$	$\rho > 0.1 \text{ m}\Omega\text{m}$

Current through the electric arc

Gases have low electric conductivity and are generally seen as insulators, but if an electric field exceeds the dielectric strength of the gas, ionisation occurs, electric current can pass, and an arc is formed. The ionized gas, or plasma, has reasonably good conductivity, so a burning arc will pass current at a relatively low voltage. Plasma can occur in vacuum at room temperature, as electrons and ions can have different temperatures. At atmospheric pressure, temperatures above 10000–15000°C, depending on composition, are required to maintain the plasma. Atmospheric-pressure plasma is commonly referred to as thermal plasma and requires electrons and heavy particles to share a temperature, which is referred to as Local Thermodynamic Equilibrium. Electric arcs at atmospheric pressure are used for industrial applications such as welding, carbon-arc lamps and electric arc furnaces. To sustain the arc, the heat dissipation associated with the current must be sufficient to maintain plasma conditions. A high current generates a high degree of ionisation and low resistivity, while a lower current is associated with less ionisation and higher resistivity. In such cases, when the voltage drop decreases with increasing current, the characteristic is said to be *falling* or *negative*. For a given arc setup, this relationship is described by the Arc Characteristic, shown in Figure 6.9. This figure shows an example of a DC-arc characteristic and a circuit for determining it. The resistance R is regulated

until a predetermined current I flows through the arc, and the voltage drop V is measured. The resulting dependence is shown as the graph 'Arc' in the figure. This graph is the *characteristic* of the arc: it shows the voltage drop for a given current in the arc.

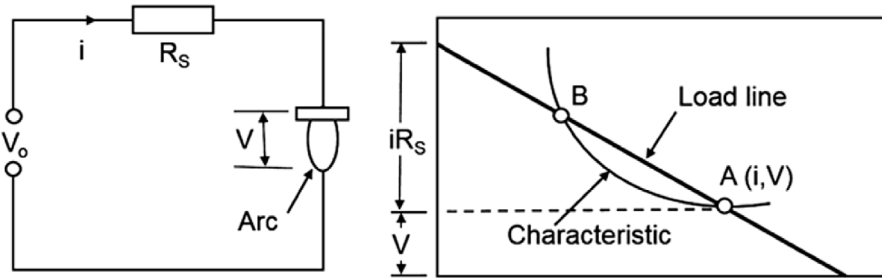


Figure 6.9 The characteristics of a direct current electric arc (b) and the main elements of a circuit for its determination (a).

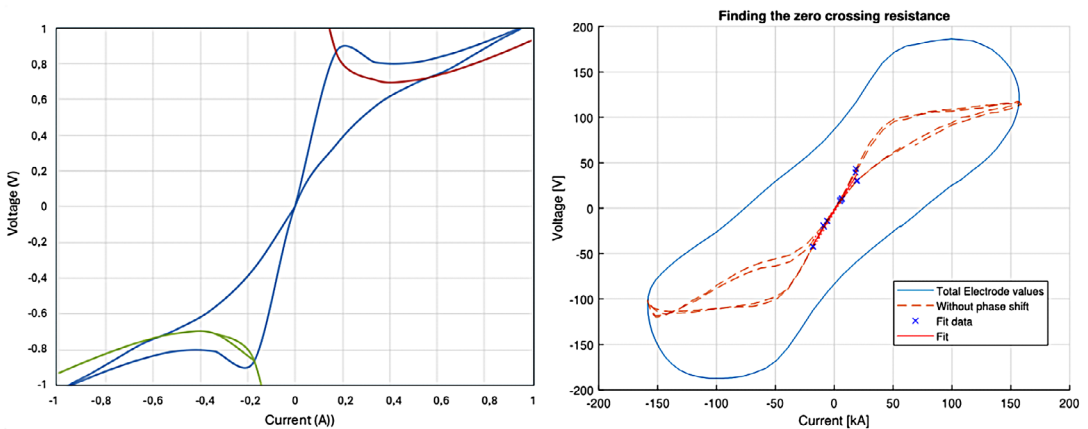


Figure 6.10 Characteristics of an alternating current electric arc, excluding reactance, often referred to as Lissajous figures, showing the voltage drop versus the current, on the left. On the right it is shown how an upper limit for the charge resistance for one phase can be estimated, from (Haraldsson et al., 2023) [Reproduced with permission from Springer Nature].

The relationship between the DC arc characteristic, which falls at lower current and rises at higher current, and the characteristics of an AC arc with the same properties is shown in Figure 6.10 (left) for normalized values. The right-hand plot shows real-time, high-resolution measurements of current and voltage at an electrode in a ferrosilicon furnace, processed to remove the phase shift due to the furnace reactance. The slope of the curve as it passes through zero can be read as a lower limit to the charge resistance for that phase, since at zero current the arc has a very high resistance.

For a normal ohmic resistance, the voltage drop increases linearly with increasing current, and the characteristic is said to be *rising* or *positive*. When the current becomes large enough, the characteristic of the arc may return to a rising characteristic; this is mostly the case at the current levels in industrial Si furnaces. In summary, for thermal electric arcs in industrial furnaces, the arc voltage does not change linearly with current because the resistance depends on current. This current dependence causes the non-linear current–voltage characteristics of arc furnaces, and the corresponding harmonics measured in the current and voltage waveforms. Figure 6.11 shows real-time, high-resolution measurements of current and voltage at an electrode in a ferrosilicon furnace, processed to remove the phase shift due to the furnace reactance (Haraldsson, 2025; Traustason, 2020). The shape of the red curves can be seen as an indicator of furnace operation, including the deviation from linearity, the area inside the curve, and the asymmetry between the positive and negative half-periods. On the left, the arc footprint for the three phases is shown, while the area enclosed by the arc in phase 2 is quantified.

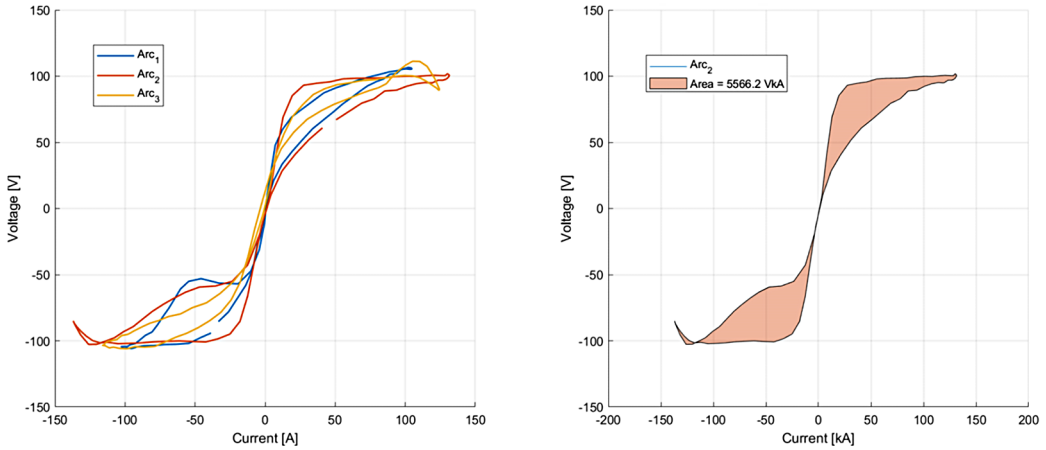


Figure 6.11 Real-time high-resolution measurements of current and voltage on an electrode in a ferrosilicon furnace, processed to remove the phase shift due to the furnace reactance. Voltage is plotted as a function of current (Haraldsson, 2025) [Reproduced with permission from Springer Nature].

Previously, it was assumed that the electric arc could be as long as half a metre, as the electrodes in a furnace often move by that amount, or more, to maintain the desired resistance. More recent data and simulation indicate that electric arcs burning in Si–O–C gas are unlikely to be much longer than 10 cm. If they are that long, there are probably more than one in parallel, based on the actual resistance level in the furnace (Sævarsdottir and Bakken, 2010).

6.3 Electrical Furnace System

In most cases, industrial Submerged Arc Furnaces used to produce silicon are three-phase, in the sense that three-phase current is passed into the furnace through three electrodes, and in exceptional cases through 6 electrodes. There are DC SAFs operated in other processes, for example ferrochromium production, but generally not for silicon production.

The high-voltage current supplied from the power transmission utility is stepped down, in two or more steps, to voltage and current levels appropriate for the furnaces. This is referred to as the ‘secondary side’ of the last transformer set, where the currents in each phase are typically in the order

of 100 kA. The circuit before the last transformation step is referred to as the 'primary side'. The high currents on the secondary side generate significant magnetic fields in the immediate area of the furnace, and this is taken into consideration for all equipment design. Ideally, the three transformers that step the voltage from the 'primary' side levels to the 'secondary' side are located symmetrically around the furnace. This practice is common because it minimizes any asymmetry in the electrical setup, which would be enhanced by the magnetic field and might have consequences for the electrical and metallurgical operations of the furnace. In some cases, for smaller furnaces with less magnetic interaction, there is one three-phase transformer that supplies current to all electrodes. The transformers are connected in a delta (D) connection to the 3 electrodes, which conduct electric power to the furnace through busbars and flexibles, and then to the contact clamps that are attached to the electrodes. This setup is called a knapsack configuration and is shown in Figure 6.12.

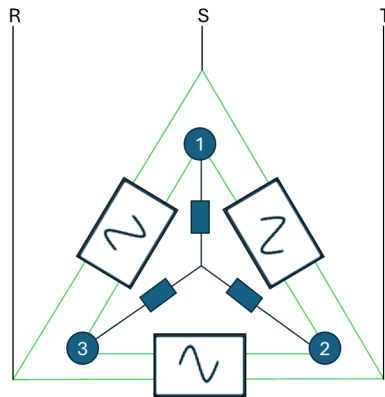


Figure 6.12 Schematic showing the electrical arrangement for a three-phase furnace, the electrodes connected in a knapsack configuration to the transformers and connected in a star connection through the furnace interior.

The three electrodes are then connected in a star connection (Y) through current paths inside the furnace. The transformers feeding current to the electrodes perform the last step-down in voltage to the operating D voltage U_D and current I_D on the secondary side of the transformer windings.

The D voltage translates to the phase voltage for the electrodes, $U_{ph} = U_{\Delta} / \sqrt{3}$, and the phase currents relate to the D currents through $I_{ph} = I_{\Delta} \cdot \sqrt{3}$. Under normal operation, phase voltages are typically of the order of magnitude of 100 V, and the currents of the order of 100 kA. The exact value depends on the size of the furnace and the raw materials. In general, larger furnaces have higher currents and lower resistances. This is associated with high magnetic field generation and inductance, which complicates furnace operation.

The furnace inductance leads to a phase shift ϕ between the current and voltage. This must be considered when calculating the real power generation in the furnace. The real power is then found by Equation [6.15]:

$$P = \sum P_{ph} = \sum U_{ph} I_{ph} \cos(\phi_{ph}) \quad [6.15]$$

The factor $\cos(\phi)$ is called the *Power Factor*, is always less than 1, and quantifies the extent to which real power generation is reduced due to reactance in the secondary circuit. For large furnaces, the Power Factor can be as small as 0.5.

The reactance in the furnace

For the sake of simplicity, let us consider a one-phase equivalent circuit representing the furnace, as shown in Figure 6.13.

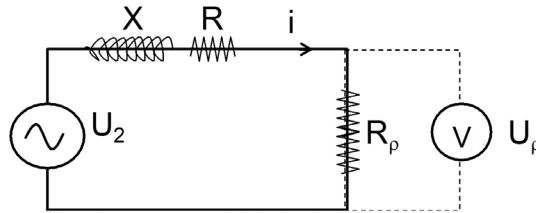


Figure 6.13 Illustration of a one-phase equivalent circuit considered as a simplification of the three-phase AC submerged arc furnace circuit.

Heat generation P due to resistive heating, as current I is passed through a resistance R , is:

$$P = I^2 R \quad [6.2]$$

On the secondary side, inside industrial furnaces, three-phase AC currents of the order of 100 kA pass through the raw materials and arcs within the furnace. Together, these make up the load-bearing resistance. The high amperage involved leads to the creation of a strong magnetic field, which generates an inductive reactance in the system. This shows up as a time delay in the accessible instantaneous voltage, due to the energy needed to build up the magnetic field.

This delay is proportional to the change in current, with the proportionality constant L :

$$u(t)_L = -L \frac{di}{dt} \quad [6.16]$$

L is called inductance and has units Henry [H]. In general, in RLC circuits, inductive reactance can be compensated by capacitive reactance, which is attributed to an accumulation of charge. In general, the contribution of capacitance to the instantaneous voltage manifests as a phase change in the opposite direction, as per equation [6.17].

$$u(t)_C = C \int i dt \quad [6.17]$$

Rather than working with instantaneous values for current and voltage, a more effective mathematical treatment uses complex numbers. Inductive reactance is defined as $X_L = \omega L$ and capacitive reactance as $X_C = 1/\omega C$, where $\omega = 2\pi \cdot 50$ Hz. *These form a combined reactance $X = X_L - X_C$ that contributes to the overall impedance Z of a circuit, such that:*

$$Z = \sqrt{X^2 + R^2} \quad [6.18a]$$

Thus, a capacitance counteracts the contribution of inductance to the impedance. For the high amperage present on the secondary side of an AC industrial furnace, it is not practical to incorporate capacitance on the furnace's secondary side, and the secondary-side impedance becomes.

$$Z = \sqrt{X_L^2 + R^2} \quad [6.18b]$$

Which, for large furnaces, can be significantly larger than R . The relationship between impedance, resistance, and reactance can be illustrated using vector plots called phasors, as shown in Figure 6.14.

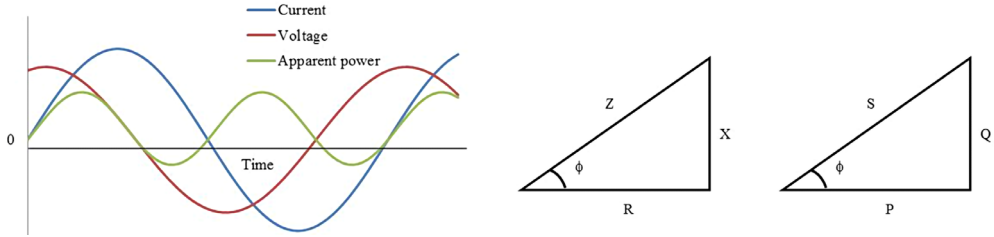


Figure 6.14 shows the relationship between instantaneous current and voltage phase shifted by angle ϕ and their product, the apparent power (left) and the vector relationship between the impedance, reactance and resistance for a circuit and the apparent power, reactive power and real power (right).

The total active power P [MW] that generates heat in the furnace is:

$$P = RI^2 = \frac{RU_2^2}{X^2 + R^2} \quad [6.19]$$

The transfer of energy associated with creating and destroying the magnetic field is denoted by the so-called reactive power, Q_L [MVA_r]:

$$Q_L = XI^2 = \frac{XU_2^2}{X^2 + R^2} \quad [6.20]$$

The furnace's electrical equipment supplies the current and voltage required to provide the apparent power S [MVA], which combines active and reactive power:

$$S = \sqrt{P^2 + Q_L^2} \quad [6.21]$$

The phase shift between instantaneous current and voltage is represented by the angle ϕ in Figure 6.14. Equation [6.19] can thus also be written in terms of ϕ , as $P = U \cdot V \cos \phi$.

The *Power Factor*, $\cos \varphi$ indicates both the extent to which the furnace circuit must be over-dimensioned to accommodate the reactive power and the level of magnetic interaction between the three phases of the furnace. Large furnaces with high amperage can have a power factor below 0.57. Magnetic interactions refer to a phenomenon in which a change in conditions in one phase causes the phase current to change. The phase currents in the other two phases then also change significantly, even though the phase resistances for those phases are unchanged. This effect is much more significant in large furnaces with small *power factors* than in furnaces with a *power factor* close to unity. One way to mitigate this effect is to apply so-called *resistance control* rather than *current control*, as was addressed in the discussion of the electrical operation of the furnace.

The operator of the grid transmitting electric power to the silicon smelter sets an upper limit on the reactive power the smelter can pull from the grid. Therefore, the factory is equipped with capacitor banks that provide capacitive reactive power, counteracting the inductive reactive power contained in the magnetic field. These capacitors are normally installed between the initial voltage step-down from the transmission voltage level, on the primary side, and the furnace transformers stepping the voltage down to the delta on the secondary side.

6.4 Energy control of the silicon furnace

The purpose of the automatic energy control is twofold: to keep the furnace at the optimum electrical conditions and to protect the equipment from damage by excessive current. In addition, the furnace can have automatic electrode slip control and metallurgical control. The slip control moves the electrode relative to the hanger to compensate for electrode consumption. For Söderberg electrodes or composite electrodes, it must also secure acceptable baking conditions for the electrode. The main purpose of the automatic metallurgical control is to provide the correct amount of carbon to the charge.

The metallurgist has two independent variables to control the electric operation:

- The voltage, controlled by the tap position of transformers.
- The position of the electrode tip (which determines the resistance of the furnace).

The position of the electrode tip is continuous, while the voltage can normally be chosen in steps over a certain range. With two independent variables, it is possible to control only two parameters.

Measurement systems

For ease of access and manageable instrumentation, phase currents are measured on the primary side of the furnace transformers in Submerged Arc Furnaces. The phase currents are measured on an equivalent circuit, which mirrors the star connection on the secondary side.

To obtain the voltage for each electrode, some furnaces have a setup installed to measure voltage between the contact clamps feeding current into the electrode and an anticipated zero point at the bottom of the furnace. In this case, a loop is used to estimate the contribution to the voltage from the magnetic field generated by the furnace. This estimated contribution is then used to compensate for the effect of induction. This method of correcting for the magnetic effect is called Bockman compensation (Bockman, 1960).

Other furnaces are controlled using voltage estimates based solely on measurements on the contact clamps. In this case, the zero-point measurement is missing. However, by assuming certain types of symmetry in the furnace, an estimate of the phase voltage is obtained. This type of instrumentation has proven relatively robust for furnace operation, although it can give erroneous results in the case of asymmetric furnace operation. Using a bottom contact provides an extra data point, which enables more accurate furnace control. This may, however, be complicated by the maintenance requirements of the Bockman compensation and by the undeniable complication that the contact point underneath the furnace is not actually the zero-point, which is moving about somewhere within the furnace. Figure 6.15 is a simplified schematic of a measurement setup for a submerged arc furnace with a bottom contact. The Bockman connection is not shown.

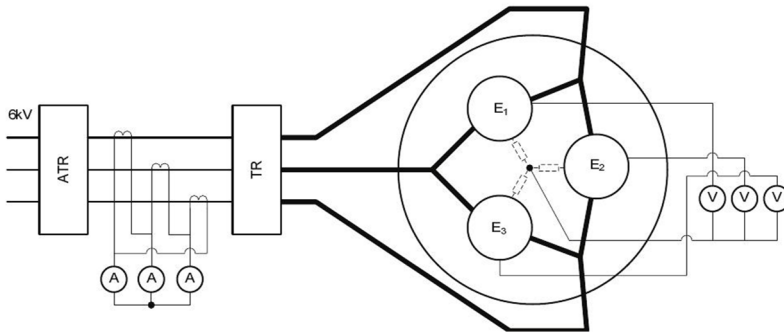


Figure 6.15 Schematic of the measurement setup of a submerged arc furnace with a bottom contact for voltage measurement (after Baron et al., 2012).

Electric operation

Since it is generally important to use the production capacity fully, the load is selected as one of the control parameters. When the load is known and the other electric parameters are determined, the optimum current can be calculated from the Westly rule, Equation [6.8]. The relation between the electric parameters can be expressed in a load nomograph, where the load is given as a function of the resistance for a set of voltage and current values. An example of a load nomograph is shown in Figure 6.16. The curves for the current have been calculated from the equation

$$P = 3 I^2 R \quad [6.3]$$

The voltage curves can be obtained from the phase voltage V :

$$P = \frac{3 V^2 \cos \varphi}{Z} = \frac{3 V^2 R}{Z^2} \quad [6.22]$$

Although the voltage listed in the nomograph is the potential between the transformers in the D, it is the phase voltage multiplied by a factor $\sqrt{3}$.

Here the impedance Z is given by.

$$Z = \sqrt{R^2 + X^2} \quad [6.18]$$

In the actual furnace, the inductance X varies slightly as the electrode moves up and down, but, for the sake of simplicity, it has been assumed constant in the furnace when creating the nomograph in Figure 6.16.

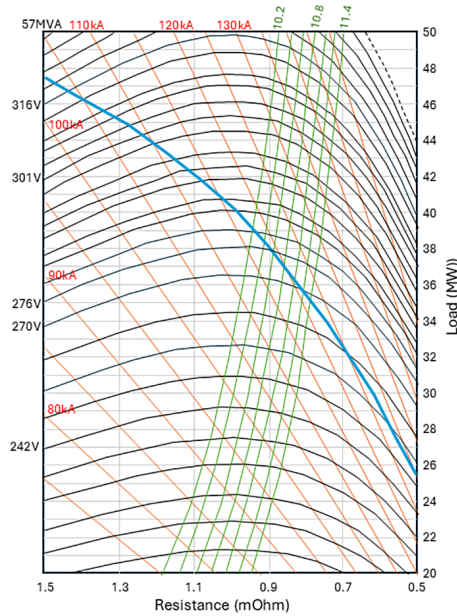


Figure 6.16 Example of a load nomograph for a fictional submerged arc furnace with symmetric load. Definition of the variables: Inductive resistance 1.00 m Ω , load for the complete furnace, current and resistance for one electrode, voltage drop between two phases at the transformer.

The use of the nomograph will be explained by an example. We want to run the furnace at a load of 37 MW, and we know from previous experience with the raw material mix that $C_3 = 10.8$ gives fairly good operation. The Westly rule Equation [6.8] then gives

$$I = 10.8 \cdot 37^{2/3} = 120 \text{ kA}$$

The nomograph gives a voltage ≈ 273 V for a current of 120 kA and a load of 37 MW. To achieve full load and optimum furnace operation, the furnace must be operated at 273 V between two phases in the secondary. If the transformers

have no step for 273 V, a nearby step must be chosen, and a middle course must be found between full load and optimum operation.

Once the transformer voltage has been set, the furnace can be controlled for either current or resistance, aiming at the optimal load.

If the furnace is controlled for current, a current setpoint is selected, and the energy controller keeps it at this value. To avoid too frequent movements of the electrodes the controller can have a dead-zone range and a defined time before action. Then the controller only acts when the current has exceeded the dead-zone bounds around the chosen setpoint for a certain time. The controller acts by raising or lowering the electrode. Then the resistance changes, and with a fixed voltage the current changes too. Figure 6.17 is a simple illustration for dead-band regulation.

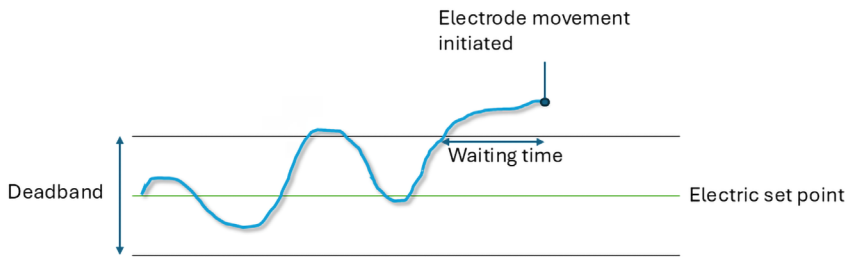


Figure 6.17 *An illustration of how a dead band regulation system works.*

In the example, the current is the control variable. Alternatively, one could control the C_3 factor, the resistance, or the impedance. Under idealized conditions these methods are equivalent, but in a real furnace they will normally differ.

Here, we have assumed that the load is symmetric, which is not always true for real furnaces. In that case, each electrode must be treated separately, and it becomes necessary to measure the voltage drop from the electrode to the bottom.

6.5 Electrode consumption

The electrodes in the furnace are consumed during operation. This must be compensated for by either adding electrode mass that continuously bakes in the furnace (Söderberg electrodes), adding prebaked blocks in the case of prebake electrodes, or using a combination of both for composite electrodes.

The electrode consumption is mostly due to two mechanisms:

- Heat load from the electric arcs, which sublime the carbon material, in particular during the anode half-period (Sævarsdóttir *et al.*, 2007; Müller and Magnussen, 1972).
- Chemical erosion due to reaction with SiO gas that flows up from the crater zone, partly along the side of the electrode, as well as chemical load from SiO₂ slag at elevated temperatures.

Sævarsdóttir *et al.* (2007) modelled possible electrode erosion from an electric arc, based on the heat load on the electrode surface from both radiation and exchange of kinetic energy with particles in the arc, as well as electrons emitted from the surface. They concluded that the erosion increased approximately parabolically with the arc current, so the contribution to the total electrode erosion was highly dependent on the current distribution between arc and charge, and on the number of arcs on each electrode. If all current on an electrode carrying 120 kA were to pass through a single arc, the erosion from the arc would be similar to typical total electrode erosion for such a furnace. They found that the erosion was much greater when the electrode serves as anode than as cathode, mostly due to the cooling effect of electrode emission in the cathodic half-period.

Otani studied the electrode consumption in a simple arc chamber and concluded that the main consumption mechanism was chemical corrosion (Otani *et al.*, 1968).

Müller and Magnussen started with the hypothesis that the electrode consumption mainly is due to evaporation at the arc spot, and they set up a fairly elaborate arc chamber to test their hypothesis (Müller and Magnussen, 1972). They reasoned that the cathode and anode drop have a fixed voltage drop, and that the heat production at the electrode spot should therefore be proportional

to the current. The rate of evaporation should then also be proportional to the current, and the electrode consumption should be proportional to the number of ampere-hours. In the arc chamber, the evaporated carbon condensed on cooler parts of the electrode, and the weight loss indicated a low electrode consumption. In further experiments, the electrode was surrounded by a coke bed that should catch the carbon vapour. The evaporation loss then became approximately the same as for submerged arc furnaces when the electrode was anode, but lower when the electrode was cathode. Some typical data for electrode consumption in submerged arc furnaces are given in Table 6.2.

Table 6.2 *Typical electrode consumptions for smelting of FeSi 75 (after Müller and Magnussen, 1972).*

Load MWA	Crater voltage V	Energy consumption	Electrode consumption			Electrical Connections
		$\frac{\text{MWh}}{\text{ton}}$	$\frac{\text{kg}}{\text{h}}$	$\frac{\text{kg}}{\text{MWh}}$	$\frac{\text{kg}}{\text{kAh}}$	
15.0	71	9.5	52	5.5	0.39	Three-phase AC
12.0	71	8.7	39	4.5	0.32	Three-phase AC
0.1	37	13.3	53	4.0	0.15	Single- phase AC
0.1	40	12.1	24	1.9	0.08	DC, electrode –
0.1	44	12.8	50	3.9	0.17	DC, electrode +

The electrode consumption reported as kg/MWh is almost the same for large and small furnaces, whereas it is lower in small furnaces when it is reported as kg/kAh. Müller and Magnussen argue that chemical consumption will be roughly proportional to production. Therefore, the observation that electrode consumption is independent of size indicates that chemical reaction is the main consumption mechanism (Müller and Magnussen, 1972). However, the strong dependence on the direction of direct current simultaneously corroborates the original hypothesis that evaporation at the electrode hot spots is important. Müller and Magnussen conclude that the question is incompletely answered, but they still think that vaporisation at the contact arc-electrode is important.

Vorob'ev and Zhuchkov pointed out that several factors influence electrode consumption, and that these can be arranged into two groups. Based on experiments in an arc chamber, Vorob'ev and Zhuchkov concluded that the arc accounted for about 10 per cent of the overall electrode consumption, and that chemical erosion accounted for the remaining about 90 per cent (Vorob'ev and Zhuchkov, 1974).

Westly stated that several parameters are important for electrode consumption, such as the quality of the electrode, the silicon content of the alloy, and the carbon content of the charge (Westly, 1985). The carbon content acts by influencing the corrosive character of crater gas.

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