

The technical silicon process

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5.1 The furnace and the plant

Over more than 100 years of silicon production, silicon plants have developed towards bigger and more sophisticated equipment, greater automatization, and better control systems, as well as the implementation of technologies for energy recovery and reduced emissions. Nevertheless, the principal process is much the same. Industrial production of silicon and ferrosilicon is normally performed in low-shaft electrical reduction furnaces. The furnace is also named a submerged-arc furnace (SAF). Installed capacity, that is, the load of the furnace, is normally used as the 'size' of the furnace. Silicon and ferrosilicon furnaces may vary in size from approximately 1 MW up to 50 MW. The furnace requires infrastructure and supporting equipment for handling large streams of raw materials, liquid and solid metals, byproducts and gases, as well as for the supply and recovery of energy. As shown in Figure 5.1, a silicon plant thus consists of several production units (Tangstad, 2013). These can be divided into the following groups.

- The furnace where the silicon and ferrosilicon production takes place.
- Raw materials, their storage, handling and supply
- The electrical system supplying energy to the furnace.
- Off-gas handling and energy recovery system
- Units for processing and handling of produced silicon and ferrosilicon
- The control system

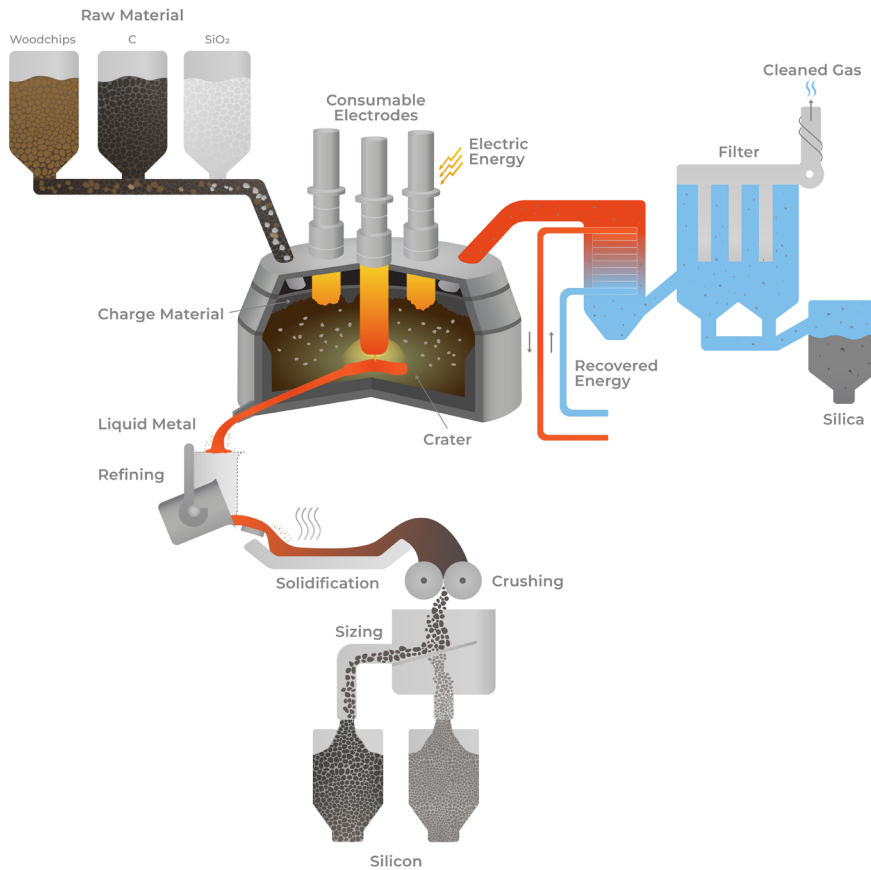


Figure 5.1 A modern ferrosilicon plant with energy recovery and gas cleaning equipment. The furnace is semi-closed, with moveable ports marked with the horizontal lines in the upper part of the furnace. (Figure redrawn by Lingyi Ren). Based on Tangstad (2013).

5.2 The processes taking place in the silicon furnace

The processes that take place in the silicon furnace form the basis for the requirements for the raw materials, the furnace, and the other parts of the silicon plant. The overall Si-producing mass balance is given by reaction [5.1]



The main raw materials are a silicon source, usually SiO_2 in the form of quartz, and a carbon reductant, most often a mixture of coal and biocarbon. Woodchips added to give a more porous charge will also contribute some carbon. In FeSi production, iron—either iron oxide or metallic iron—is another important raw material. Other raw materials, for instance limestone, may also be used, depending on the case.

Furnace excavations have established a schematic picture of the inner structure of Si and FeSi furnaces (Ksiazek *et al.*, 2016). As shown in Figure 5.2, they can be divided into four main reaction zones: the pre-reaction zone, the reacting materials, sometimes a SiC crust, and the cavity. In addition, there is the metal bath at the bottom of the cavity, and the inactive slag zone, consisting mainly of slag, along the furnace walls.

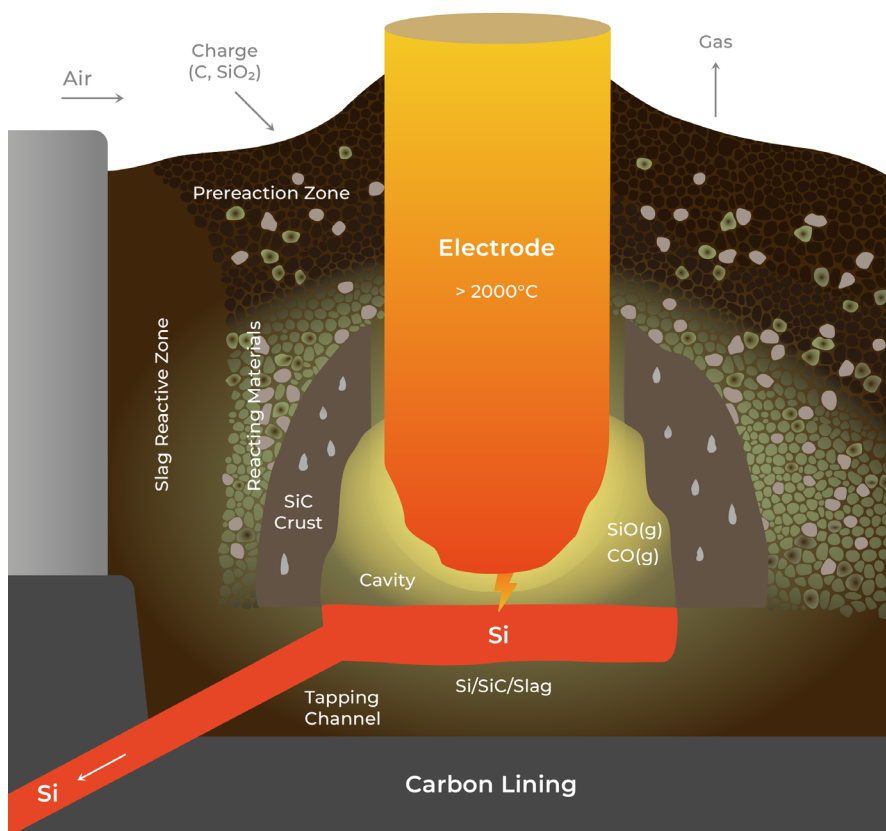
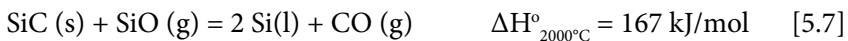
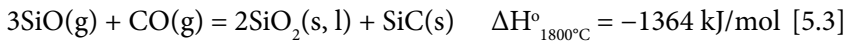


Figure 5.2 Reactions and reaction zones in Si furnace. (Graphics: Lingyi Ren).

The raw materials – the charge mixture with quartz and carbon source as the main constituents – are fed semi-continuously to the top of the pre-reaction zone (the charge top), where the temperature is around 700–1300°C (Johansen *et al.*, 1998). Liquid Si, at approximately 1900 °C (Ksiazek *et al.*, 2018), is tapped out at the bottom of the furnace. Off-gas, composed mainly of CO and SiO, leaves the pre-reaction zone at the charge top, where it burns with air to CO₂ and SiO₂. To obtain a high silicon yield, the off-gas must have a low SiO content. To obtain good furnace performance, there must be an even gas flow and good charge permeability in the furnace.

Quartz descends in the furnace and is reduced to SiO by reaction [5.5] and [5.6]. These reactions take place in the pre-reaction zone, the reacting materials zone, the SiC crust, and in the cavity at the top of the metal bath. The produced SiO will either react with carbon to β-SiC by reaction [5.4] in the pre-reaction zone or the reacting materials zone in the upper parts of the furnace. SiO will also react with SiC to Si by reaction [5.7] in the SiC crust or the cavity, where the temperature is higher. SiO gas that is not consumed by reaction [5.4] will either be captured in the charge by reaction [5.2] and [5.3] in the pre-reaction zone, or leave the charge mixture at the top of the furnace, followed by a decreased Si yield.



Energy is supplied through the three electrodes, as described in Chapter 6. An electric arc is formed between the lower part of the electrode and either the metal bath or the SiC crust, forming a cavity around the electrode tip. Plasma in the cavity has a temperature higher than 3000 °C, which heats the

cavity walls (the SiC crust) by radiation. Electric current through the SiC crust generates additional energy for heating of the SiC crust and for endothermic reactions that take place in this zone. Here, the temperature is assumed to be more than 2000 °C. Tapped metal, both from Si and FeSi furnaces, has a temperature of around 1900 °C (Ksiazek *et al.*, 2018). The metal bath has at least this temperature inside the furnace.

Materials above the SiC crust are mainly heated by warm ascending gases generated in the lower zones in the furnace (the cavity and the SiC crust) and by exothermic reactions that take place higher up in the furnace. Back reactions with SiO – reactions [5.2] and [5.3], which are highly exothermic – are, together with reaction [5.4] (between SiO and C), the main contributors. Reactions in the material reaction zone with volatiles from carbon materials, and evaporation of water in woodchips and other raw materials, will also contribute to the temperature profile in the furnace. Burning of SiO and CO gas to SiO₂ and CO₂, above the charge top where oxygen is available, develops energy that gives a high off-gas temperature. The temperature can also be increased in a thin layer just below the top of the charge due to in-flow of oxygen in the materials at the top of the pre-reaction zone. Below the charge top, where oxygen is not present, the temperature decreases and is measured at around 600°C (Ksiazek *et al.*, 2021; Saadieh, 2024). Further down, the temperature will increase with depth. Modelled temperature profiles for selected Si and FeSi furnaces (Ringdalen *et al.*, 2019), though not valid for the upper, low temperature zones in the furnace, also indicate that the temperature does not increase linearly with increasing furnace depth. The raw materials are heated fast up to around 1600°C in the upper part of the furnace, in the pre-reaction zone and the upper part of the material reactions zone. In most of the furnace volume above the cavity, the temperature is between around 1600°C and 1800°C. An average heating rate of 5.5 °C/min and a material flow of around 0.3 m/hour has been estimated as normal for Si furnaces (Ringdalen *et al.*, 2019). In a 45 MW Si furnace, around 8000 Nm³/h of gases is generated by the reaction in the furnace, giving a gas velocity in the material reaction zone of around 1 m/s (Nordhus, 2022). To have an even flow of gas, the material bed in these zones must have a high enough permeability. This limits the amounts of fines that can be present in the charge. The amount of fines in raw materials fed to the furnace, and generation of fines during their processing in the furnaces, are thus restricted as a part of raw material requirements.

SiO gas produced by the endothermic reaction [5.5] and [5.6] at high temperatures in the cavity and SiC crust will ascend to the reacting materials zone and pre-reaction zone, where the temperatures are lower. SiO will then react back to SiO_2 and SiC or Si by reactions [5.2] and [5.3], which are exothermic. Energy used in the cavity and SiC crust for reduction of SiO_2 to SiO by the endothermic reaction [5.5] and [5.6] will thereby be released in the material reaction zone and pre-reaction zone when SiO reacts back by reactions [5.2] and [5.3]. The extent depends on the amount of ‘circulating’ SiO. This transport of energy from the cavity and SiC crust to the reacting materials zone gives less energy available for final Si production in the SiC crust and cavity and is thus unwanted. This is discussed in more detail in Chapters 3 and 7.

To obtain a high silicon yield, reduction of SiO_2 to SiO by reaction [5.5] and [5.6] should take place at the higher temperatures in the cavity and SiC crust, where SiO gas is needed for the final production of Si by reaction [5.7]. A slow reaction rate for reaction [5.5] and [5.6] in the material reaction zone higher up in the furnace, where the temperature is lower, is thus preferred. SiO is produced at high temperatures in the cavity by reaction [5.5] when quartz pieces fall or molten quartz drips into molten Si in the crater, and by reaction [5.5] and [5.6] in the SiC crust and at the crater walls. SiO gas ascending from the crust will, in the material reaction zone, meet descending carbon and, at temperatures above around 1500 °C, and react with this to β -SiC according to reaction [5.4]. Complete conversion of carbon to SiC is crucial to achieve a high Si yield. Produced β -SiC will descend further down in the furnace and, in the SiC crust at temperatures above around 2000 °C, be transformed to α -SiC, which is the SiC polymorph found in the SiC crust. The final product, Si, is produced in the SiC crust and at the crater walls by reaction [5.7] between SiO and α -SiC. Produced silicon or ferrosilicon accumulates below the crater zone at the bottom of the furnace. It is tapped out through tap holes that are drilled through the lining.

When ascending SiO gas reacts back according to reaction [5.2] at lower temperatures in the material reaction zone, it will form a mixture of fine-grained SiO_2 and Si called brown condensate, while SiO gas that reacts with CO according to reaction [5.3] will form a fine-grained mixture of SiO_2 and SiC called white condensate. Condensates are abundant in the material reaction zone above the SiC crust, with brown condensates being most common. The condensates will glue the raw materials together, creating the so-called ‘condensate layer’. To enhance gas flow from the lower to the upper part of the

furnace, and material flow downwards in the furnace, the condensate layer is regularly broken up with mechanical stoking from the top of charge.

Unreduced oxides in the raw materials, such as CaO and Al_2O_3 and others, will form a slag. Due to the relatively low amounts of these oxides in the raw materials, the amount of slag per ton of alloy is relatively low. A small amount of slag is tapped out together with the alloy. Slag may also accumulate in the more inactive zones in the furnace and form a slag layer: a slag zone along the walls of the furnace and, in some cases, below the metal at the bottom of the cavity. Slag formation and its effect is discussed more in detail in Chapter 8.

5.3 Raw materials for silicon and ferrosilicon production

The main raw materials for current industrial Si and FeSi production are:

- Si-sources, normally one or several quartz sources.
- Reductants, various carbon sources.
- Iron sources for FeSi production, such as metallic iron or iron oxides.
- Wood chips to improve charge properties.

Smaller amounts are also used of:

- Additives for adjusting product quality and for refining.
- Recirculated internal and external waste materials.

The main raw materials are generally abundant. However, to be used in Si and FeSi production, the raw materials must meet specific criteria, which limits the available sources. Selecting suitable raw materials is therefore an important task in optimising Si and FeSi production. Raw material properties affect product quality, process performance and emissions.

Effects on product quality

The amount and type of contaminants that can be tolerated in the raw materials depend on the specific product. Silicon, and especially solar grade silicon,

requires pure raw materials, which limits raw material choice. The content of contaminants varies between different raw material sources. As illustrated in Figure 5.3, product quality is the result of the sum of each contaminant in all the raw materials and of the extent to which they end up in the product. The distribution of each contaminant between the different phases, and its content in the final product, can be calculated by a mass balance, where the distribution between the products is estimated or found using the boiling point model, as also discussed in Chapter 4 (Kero *et al.*, 2019; Myrhaug, 2003). In addition, electrodes contribute minor elements to the product. The relative importance of quartz, coal and electrodes to P, B and Fe content in solar grade silicon is illustrated in Figure 5.4 for a specific case (Myrhaug, 2003).

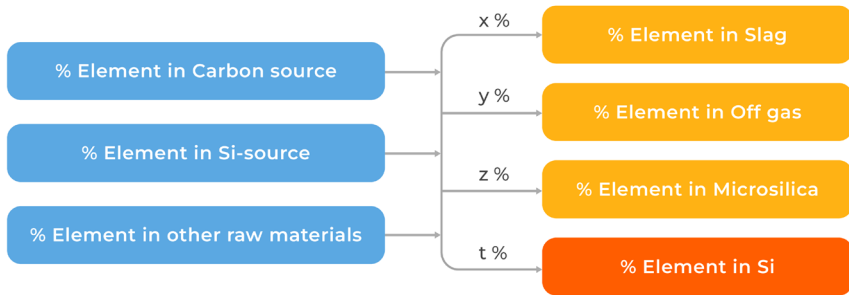


Figure 5.3 *Effect of raw materials on product quality.*

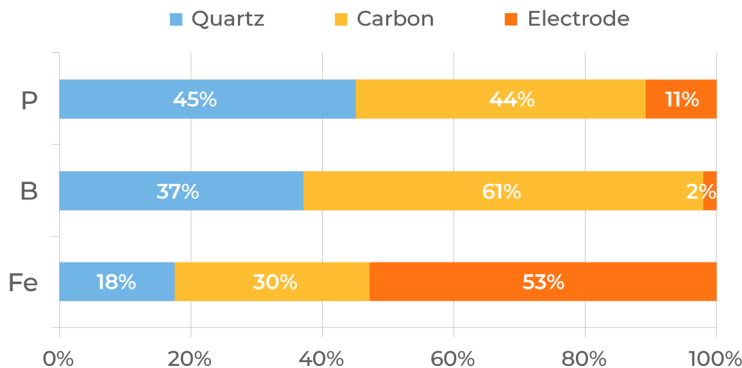


Figure 5.4 *Relative contribution of P, B and Fe from quartz, carbon and electrodes to solar grade silicon (Myrhaug, 2003) (Redrawn by: Lingyi Ren) [With permission L.V. Myrhaug].*

Raw material sizing

The required size and size distribution vary between raw materials, depending on their densities and required reactivities. The choice of size distribution also depends on the availability and cost of different fractions. Particles must be in a size that can be handled by the local material-handling and charging system. In addition, the minimum size must be limited to prevent raw materials being blown off from the charge top by the ascending off-gases. Loss of raw materials to the off-gas system increases raw material costs, but it may be more severe when it changes the carbon coverage. Wide size distributions, or large differences in sizing between different raw materials, may cause segregation and should therefore be avoided when this is not wanted. (Ringdalen *et al.*, 2022)

Reactions in a 20 MW Si furnace will develop around $1.3\text{Nm}^3/\text{s}$ of gas (Tveit *et al.*, 2020). Gas flow depends on the available area, but will be around 0.67 m/s at $1800\text{ }^\circ\text{C}$ in the high-temperature zone in a 40 MW Si-furnace. The size distribution of raw materials must be within a range that ensures an even, well-distributed flow of gas through the material reaction and pre-reaction zone, up to the charge top. Build-up of high pressure and gas blows are mainly caused by the condensate layer (Tveit *et al.*, 2020) and by fine particles, less than around 2 mm (Ringdalen *et al.*, 2022).

The size distributions of raw materials in the furnace are normally different from the size distribution specified when they are purchased. As illustrated in Figure 5.5, raw materials disintegrate and generate fines during mining, transport to and handling at the plant, when they are fed to the warm charge top, and during heating in the furnace. The extent of fines generation at each step varies with raw material type and source.

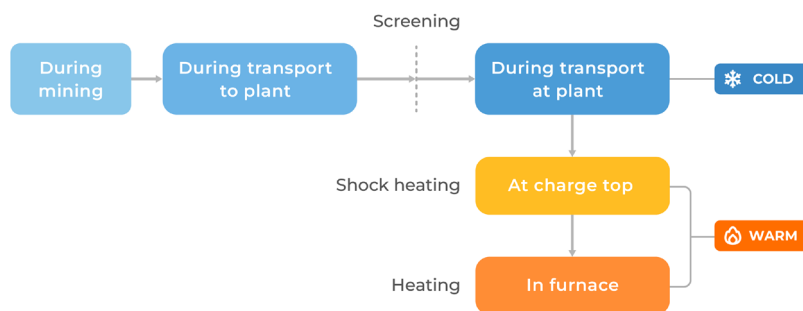


Figure 5.5 Fines generation from raw materials in different steps during handling and processing.

Silicon source – Quartz

Sources

The main silicon source is the mineral quartz, SiO_2 . The main quartz sources are rocks such as quartzite, hydrothermal deposits, pegmatitic quartz and fluvial deposits. Normally, sources with a high content of SiO_2 , above 98%, are used without any upgrading. At the mine, the quartz source is screened to the designated size, normally 10–150 mm, before it is shipped to the plant. Norwegian Si and FeSi producers use quartz both from national quartz sources and from quartz sources all over the world.

Role and effects in process

Silicon is produced from quartz by first reducing the quartz by reaction [5.5] and [5.6] to SiO , which is further reduced to Si by reaction [5.7].



Final production of SiO takes place in the high temperature zone, around 1800°C. It is therefore preferred that most of the SiO is produced at high temperature, and that the reduction of quartz is slow at lower temperatures. The reaction mechanism is not well understood, but the reaction rate does not seem to depend on the quartz source itself (Folstad *et al.*, 2021; Sindland and Tangstad, 2021; Tangstad *et al.*, 2019). The reaction rate to SiO will, however, increase with decreasing particle size. Melting gives a higher contact area towards SiC and may increase the reaction rates. A large particle size and a long time to obtain final melting may thus be beneficial, as they promote reduction of quartz in the lower part of the furnace. At the same time, a large temperature interval between softening and melting may result in clogging in a large volume of the furnace, which is unwanted (Ringdalen *et al.*, 2019).

Properties

At 25 °C, the density of quartz is 2.65 g/cm³. The melting point is approximately 1720 °C. In nature, SiO₂ is found in the form of the polymorph α -quartz. During heating, this is transformed to other polymorphs: β -quartz at 573°C and then, through an intermediate amorphous phase, to cristobalite (Jusnes, 2020; Ringdalen, 2015, 2014). The rate of transformation from β -quartz to amorphous SiO₂ and further to cristobalite varies considerably between different industrial quartz sources (He *et al.*, 2021; Jusnes, 2020; Ringdalen, 2014; Ringdalen and Tangstad, 2016). The transformation takes place through nucleation, which starts throughout the whole quartz particle. No correlation has been found between the content of different polymorphs and thermal strength (Jusnes, 2020), the reaction rate with SiC (Tangstad, 2019; Folstad, 2021), or the reaction rate with Si (Sindland, 2020). The change in structure is accompanied by a decrease in density, and the volume of SiO₂ increases by more than 20% during heating up to melting (Ringdalen, 2015).

Fines formation during handling and use of quartz varies between different sources, due to differences in both cold and warm strength (Jusnes *et al.*, 2018a). Warm or thermal strength includes both strength during heating for longer time, simulating heating in the charge mixture (TSI-Thermal Strength Index), and strength towards thermal shock when the materials are fed to the warm charge top. Fines generation will increase with increasing grain size, increasing number of cracks, and decreasing amount of muscovite in the quartz source (Jusnes, 2020). Both TSI and fines generation by thermal shock vary considerably between different quartz sources.

The melting temperature of quartz, around 1720°C, will be lowered by the content of minor elements such as alkalis (Dalaker, 2025). As an example, a silica source with 0.2% K₂O and no other contaminants will form the first molten phase at 770°C (solidus), while the temperature for complete melting (liquidus temperature) will only be lowered by around 5°C. Formation of the first melt will, at around 1600–1700 °C, make the particles start to soften (Ringdalen *et al.*, 2019). They will then become sticky and clog together, or with other solid materials. This will affect the downward material flow in the furnace. Quartz needs, in contrast to most materials, to be superheated before it is completely molten. The required time at the melting point, at the solidus temperature, or at higher temperature until complete melting is obtained varies, as illustrated in Figure 5.6, between quartz sources and can be several

hours (Ringdalen *et al.*, 2019). The mechanism behind the superheating and differences in melting properties is not completely clear, but the content of minor elements, as well as the high viscosity of molten silica, are indicated to play a role. In industrial Si and FeSi furnaces, quartz will thus be softened or partly molten in most of the charge volume that has a temperature between 1500°C and 1800°C.

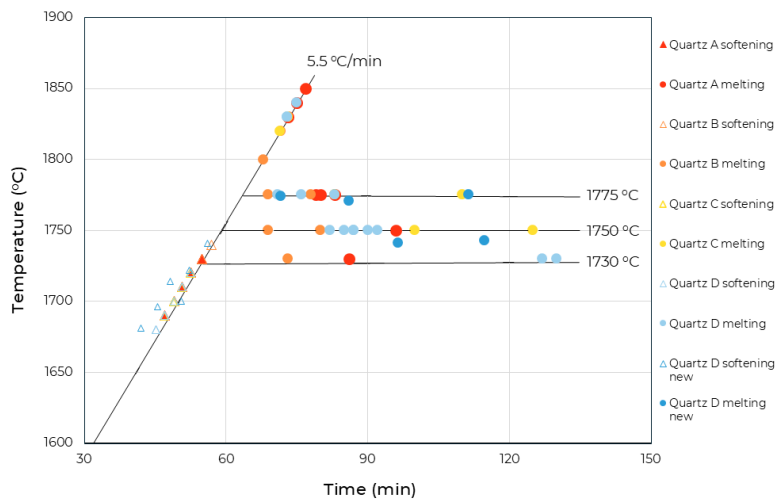


Figure 5.6 Temperature and time needed for complete melting of different quartz sources (Adapted from Ringdalen *et al.*, 2020).

Liquid silica has a viscosity of around $2 \cdot 10^7$ Poise at the melting temperature, which is nearly the same as the softening point for glass and 10^9 times higher than the viscosity of liquid silicon. It will thus behave almost as a solid. The viscosity decreases rapidly with increasing temperature and is around $5 \cdot 10^4$ Poise at 2000°C. It is also affected by the content of other elements in the silica melt. Around 0.5–1% of contaminants, such as FeO, Al_2O_3 and CaO, will lower the viscosity by around 50–70%, with Al_2O_3 having the greatest effect.

Softening of quartz that clogs particles together is expected to have a negative effect on the flow of solid silica downwards in the furnace. The flow rate for molten silica is expected to increase as viscosity decreases. The rate of reactions involving silica will change during melting, as in reaction [5.6], where it decreased around the melting temperature and increased when the silica was completely

molten (Andersen, 2010; Andersen, 2009). Reaction rates are also expected to increase with decreasing viscosity. Differences between quartz sources in melting properties and in the content of minor elements that change viscosity are therefore expected to lead to differences in material flows and the rate of SiO production in the furnace. This may, in a transition period, give differences in furnace performance when the quartz source is changed, and may in some cases make it necessary to adapt operational parameters to the quartz source.

Quartz requirements

Requirements for the quartz depend on the specific product, the properties of the other raw materials, the operational strategy and the furnace design. The required maximum content of the various contaminants must be decided based on the product requirement and their content in the other raw materials. Low fines generation, i.e., high cold and warm strength and resistance towards thermal shock, is also important. A slow rate for SiO generating reactions [5.5] and [5.6] at temperatures below around 1800 °C will be beneficial. This ensures that most SiO is generated in the high temperature zone of the furnace, where it can be further reduced to Si. A relatively large particle size, around 10–50 mm, contributes to this. Melting properties may affect furnace operation, but their effect results from an interaction between several properties and is not yet quantified.

Test methods

There is no standard furnaceability test for quartz. However, some methods for measuring specific properties are used. Warm strength during longer heating is measured by the TSI (Thermal Strength Index) test (Aasly, 2008; Aasly and Dosaj, 2016; Ringdalen and Tangstad, 2016). This is a standard test in which the materials are heated for 30 minutes at 1300°C, and fines generation is then measured both after heating and after further tumbling. Several slightly different methods have been used. Resistance towards thermal shock is measured by dropping a 200-gram sample into a crucible preheated to either 1300°C or 1500°C, holding it there for 10 minutes, and measuring the resulting size distribution (Jusnes *et al.*, 2018b). Melting properties can be measured by a sessile drop apparatus (Nordnes, 2019; Ringdalen *et al.*, 2019).

Reduction materials

Sources

Traditionally, a mixture of different solid carbon reductants has been used in Si and FeSi production. Coal has been a main source, but petcoke and char, as well as metallurgical coke and several others, have also been used, as illustrated in Figure 5.7. Woodchips are added to obtain a more porous charge, but they also contribute to the carbon content in the charge mixture.

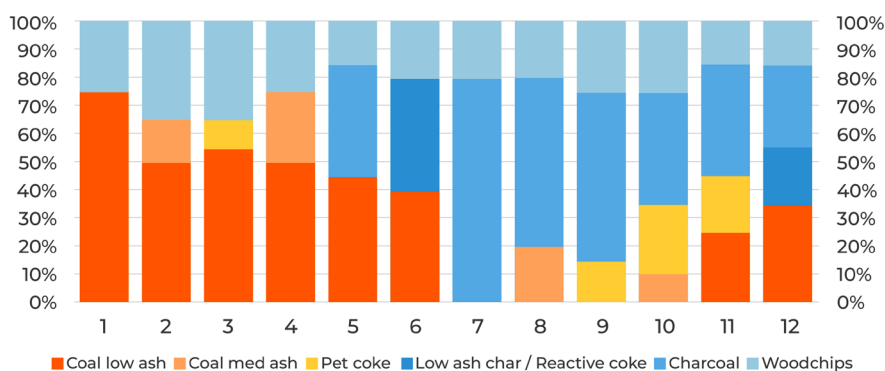


Figure 5.7 Twelve carbon mixtures used in silicon production where numbers indicate various producers. (Myrvågnes, 2008) (Redrawn by Lingyi Ren) [Used with permission from V. Myrvågnes].

Biobased reductants are increasingly substituting fossil carbon to reduce fossil CO₂ emissions. This forms part of the sustainability strategy for several producers¹ (Lindstad *et al.*, 2010). Both commercial biocarbon and designed biocarbon materials have been investigated and developed. South American Si and FeSi producers have traditionally used a large percentage of charcoal, often only charcoal in addition to woodchips (Sommerfeld *et al.*, 2021). Their charcoal is often made from eucalyptus grown on their own plantations. For coal to Si-production, Colombian coal is an important source for many producers.

1 https://www.prosess21.no/contentassets/d4c74305ab764cf2b24f3f61f0514f5d/prosess21_rapport_hovedrapport_web-1.pdf

Role and effects in process

Carbon is present in silicon at ppm levels, while ferrosilicon contains a higher level of carbon. The main part of the carbon will therefore generate CO₂ emissions, which is an environmental problem. Carbon is, however, necessary for production and has two crucial functions in the Si-process. Its main role is as a reductant, removing oxygen from SiO₂ and converting it to Si. As described above, in Section 5.1 and in Chapter 3, this is accomplished through a set of sub reactions. In addition, as a constituent in SiC, carbon is important for electrical conductivity and energy distribution in the furnace (Hoover, 2023). The properties of the carbon materials affect Si production and the operation of Si furnaces in different ways (Tangstad *et al.*, 2025):

- Generation of dust during transport and handling
 - Due to low cold strength
- Loss of fine particles of carbon to off gas
 - Due to low strength towards shock heating
- Off-gas composition and amount
 - Due to volatiles, moisture and contaminants that go to gas
- Rate for distribution of and variations in material and gas flow
 - Material flow is affected by volume of required carbon materials, which is determined by bulk density and % FixC of the carbon material
 - Gas flow is affected by the charge permeability, which depend on amount of fines in the charge and due to low thermal strength
- Furnace performance, energy consumption and yield
 - Important carbon properties are SiO reactivity and electrical conductivity
- Alloy quality

Carbon properties

Typical properties of some carbon reductants are given in Table 5.1.

Table 5.1 *Typical properties of some carbon reductants (Jayakumari et al., 2023).*

	Coal	Calcined coal (1200°C)	Charcoal	Pet-coke	Metallurgical coke
Fixed carbon (%)	58.36	91.9	90.32	89.8	86.10
Volatiles (%)	40.58		8.06	10	1.39
Ash (%)	1.06		1.62	0.2	12.51
Ash composition					
SiO ₂ (%)					46.7
TiO ₂ (%)		0.84	0.02	0.24	
Al ₂ O ₃ (%)		25.9	0.4	7.0	34.45
Fe ₂ O ₃ (%)		11.4	0.5	13.1	7.7
CaO (%)		2.7	47.0	17.1	4.6
MgO (%)		1.8	6.0	1.3	0.6
MnO (%)		0.09	3.20	0.75	0.11
Na ₂ O (%)		2.30	0.20	4.40	0.49
K ₂ O (%)		0.38	13.20	0.14	0.54
P ₂ O ₅ (%)		0.27	5.50	0.52	
S (%)					0.80
P (%)					0.23
Bulk density (g/cm ³)		0.35–0.46	0.23–0.30		0.9–1.1
Porosity (%)		38–57	70–82	±20	44–55
CO ₂ reactivity (%FixC/s)			2.1–2.3×10 ⁻²		0.2–0.5×10 ⁻²
Thermal abrasion strength: T.I.3 (%)		84	78–82		78–88

Chemical composition is, in most cases, the first property considered when choosing a carbon source. As illustrated in Figure 5.3, the required chemical composition for carbon materials depends on the requirements for the actual product and on the composition of the other raw materials. For Si, the B and

P content are often important constraints. The choice of carbon materials is also important for the environmental performance of the process. In addition to contributing to CO₂ emissions, carbon materials often contain sulfur and other unwanted tramp elements. If the carbon source contains mercury, this will evaporate in the process and be emitted into the environment with the off-gas. The accepted content of heavy metals and other emission elements depends on the installed gas treatment at the actual site.

The generation of fines during transport and handling, and due to heating inside the furnace, may lead to dust generation (Jahrsengene *et al.*, 2023) and to loss of carbon materials through the off-gas system. Uncontrolled carbon losses to the off-gas system will affect the carbon coverage of the furnace and have a negative impact on furnace performance. High cold and thermal strength is critical to avoid fines generation and is thus an important carbon property (Jayakumari *et al.*, 2023; Lindstad *et al.*, 2010; Monsen *et al.*, 2007). As seen in Figure 5.8, this will vary between carbon sources. Charcoal is more fragile than other carbon sources and therefore generates more fines. Increased fines and dust generation are among the challenges when biocarbon, which has lower strength, substitutes other carbon sources.

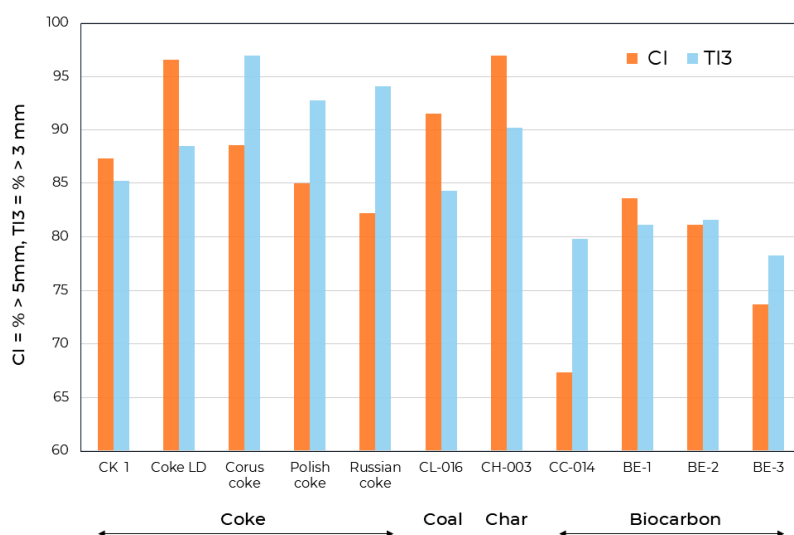


Figure 5.8 Thermal strength of various carbon materials (CI is after CO₂ oxidation and TI are after subsequent tumbling). Adapted from values (Jayakumari *et al.*, 2023).

In the charge zone in the upper part of the furnace, the descending carbon materials are heated by the ascending gases, and volatiles and moisture are driven off. Below, in the reacted charge, carbon materials react with ascending SiO gas according to reaction [5.4], producing SiC needed both for SiO generation and for final Si production in the lower part of the furnace.



This reaction both captures SiO gas, reducing SiO loss, and converts carbon to SiC, which is required for final Si production. To capture as much SiO gas as possible and to have SiC available for final production, it is beneficial to use a carbon material that reacts easily with SiO gas. Carbon materials with a high rate of reaction with SiO, high SiO reactivity, and complete conversion of carbon to SiC are among the most important process parameters in the Si-process (Lindstad *et al.*, 2007; Suárez-Ruiz *et al.*, 2019). Both practical experience and laboratory measurements have shown that the ability of carbon to react according to reaction [5.4] is highly dependent on the carbon source and its properties. Charcoal normally has a higher SiO reactivity than coal, coke, and other carbon sources, and will therefore, with the same SiO content in the gas, capture more SiO gas than coal or coke during the same exposure time. Typical SiO reactivities are shown in Figure 5.9.

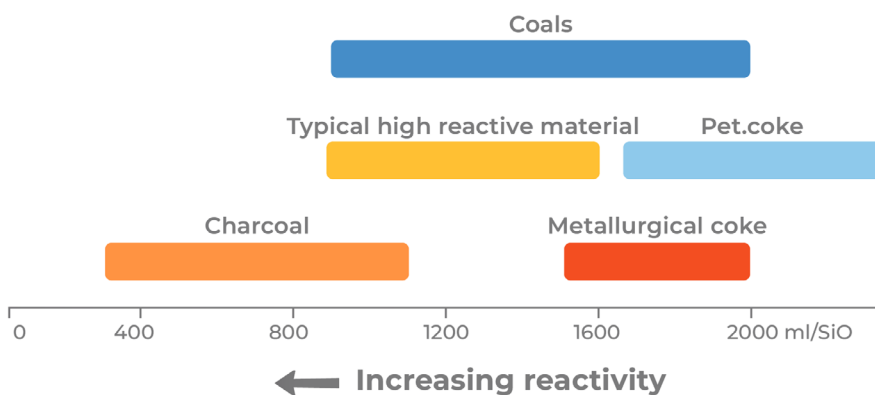


Figure 5.9 SiO reactivity of different carbon materials where a lower number of SiO gas not reacting signifies a high SiO reactivity (adapted from Raaness and Gray, 1995) [Used with permission from M. Raaness].

The reaction between carbon and CO_2 , the CO_2 reactivity of the carbon materials (reaction [5.8]), can be measured by various methods. It is often given as the Carbon Reactivity Index (CRI) by carbon material suppliers ('ISO:18894:2006', 2006). This test is based on fine-grained particles reacting with 100% CO_2 , which is far from conditions in Si/FeSi furnaces. The conditions in the Sintef CO_2 reactivity test (Ksiazek *et al.*, 2022; Tangstad *et al.*, 2025), where larger particles are exposed to a gas with 50% CO + 50% CO_2 , are closer to the conditions in industrial furnaces, although no SiO is present in the gas atmosphere. Further references to CO_2 reactivity are based on measurements using this method.



In Si and FeSi production, the temperature in the charge in most of the furnace is so high that very little CO_2 is expected to be present in the gas phase, and CO_2 reactivity is therefore probably of little importance. A correlation between SiO reactivity and CO_2 reactivity has been postulated, but, as seen in Figure 5.10 a), only a grouping into different values for the various sources can be found, and not a correlation within these groups. When carbon reacts with CO_2 (reaction [5.8]), only gas is produced, while the reaction between carbon and SiO (reaction [5.4]) generates, as discussed in Chapter 2, a solid SiC layer in addition to gas. High porosity in carbon materials, such as in biocarbon, is therefore expected to have less effect on SiO reactivity than on CO_2 reactivity. This can be seen by comparing the correlation between SiO reactivity and porosity shown in Figure 5.10 b) with the correlation between CO_2 reactivity and porosity shown in Figure 5.10 c) (Jayakumari, 2020; Jayakumari and Ringdalen, 2022).

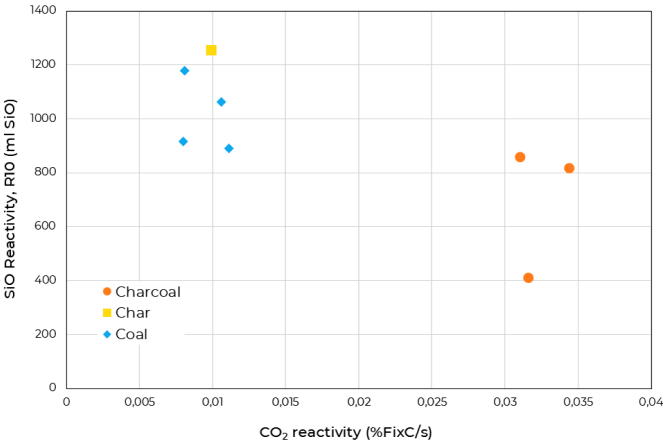


Figure 5.10a Correlation between SiO reactivity, measured by SINTEF SiO. Reactivity test and CO₂ reactivity. Adapted from (Jayakumari and Ringdalen, 2022).

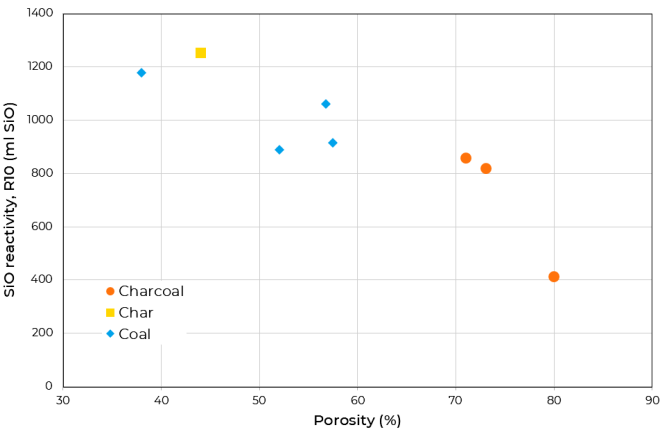
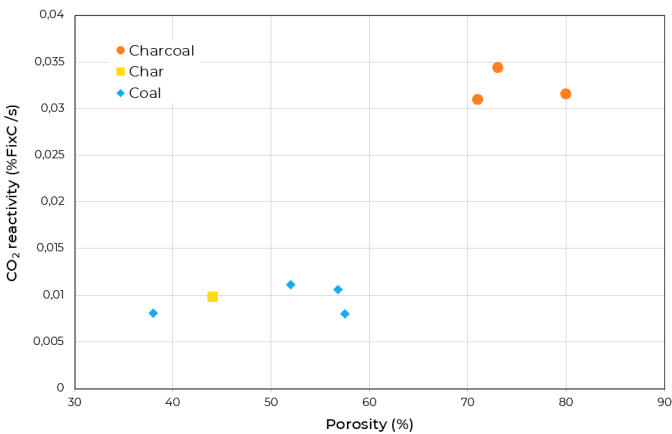


Figure 5.10b,c Correlation between porosity and b) SiO reactivity measured by SINTEF SiO-reactivity tests and c) CO₂ reactivity. Adapted from (Jayakumari and Ringdalen, 2022).



Reaction [5.4] between SiO-gas and carbon takes place at temperatures around 1500 °C to 1800 °C, producing β -SiC. This is converted to α -SiC as it descends into the high-temperature zone. SiC properties, and how fast it reacts with Si, are affected by the properties of the original carbon material. At the same temperature, more Si will be produced from SiC originating from charcoal than from SiC produced from coal (Jayakumari, 2020).

For good energy distribution in the furnace, it is beneficial that most of the currents go low down in the furnace. This requires high electrical conductivity and low electrical resistance in this zone. Electrical resistivity varies with the type of carbon materials in the charge mixture and the extent of their further transformation to SiC, as seen in Figure 5.11 (Hoover, 2023). Charcoal has a higher resistivity than coal and char. SiC has a higher resistivity than carbon, with partially transformed SiC having the highest resistivity but decreases slightly with content of Si. All carbon materials have higher resistivity than pure liquid Si. Since the total resistance is dominated by the contact resistance between particles, particle size has a major effect on overall resistance in the furnace.

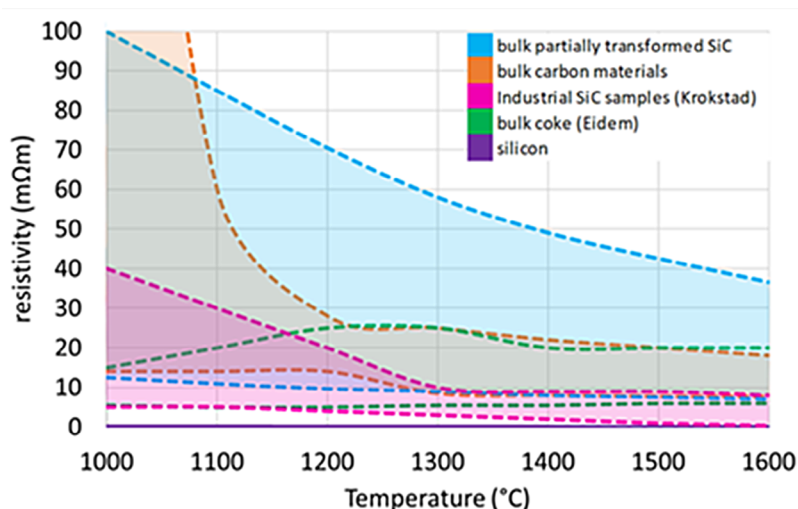


Figure 5.11 Electrical resistivities of carbon materials, SiC and Si (Hoover, 2023). [Reprinted with permission from H. Hoover].

Requirements to carbon materials

The main requirements for carbon materials for Si production can be summarized as

- Suitable chemical composition
 - low content of contaminants such as P, B, Fe, S and others
- High mechanical strength at cold and warm conditions
- High SiO reactivity
- Suitable (high) electrical conductivity
- High density

Test methods

Several methods are available to measure critical properties of carbon materials used in ferroalloy production (Smith-Hanssen *et al.*, 2023). For the Si process, the main dedicated measurement method is the SINTEF SiO-reactivity test (Lindstad *et al.*, 2007). In this test, the reaction rate between SiO and carbon is measured at 1650°C in an Ar–CO–SiO gas mixture with 13.5% SiO and 4.5% CO. Under these conditions, the reaction between SiO and C has a relatively slow rate. Differences between carbon materials are therefore more easily observed, but the measured SiO reactivities will not necessarily represent the reaction rate in industrial furnaces. Relative reactivities measured by the SINTEF SiO reactivity test for some common carbon sources are given in Figure 5.9.

Wood chips

Woodchips are included in the charge mixture for silicon and ferrosilicon production by many producers, but at a low percentage, often lower than 10%. With a low Fix C content of around 10–20%, woodchips make only a minor contribution to the carbon content needed for reduction (Andersen *et al.*, 2023; Monsen *et al.*, 2001; Ringdalen and Gaertner, 2024). Woodchips are therefore mainly added not as a reductant, but to improve material and gas flow in the charge mixture (Saadieh, 2024). The low density and flat shape of wood chips contribute to high charge porosity, giving a more even gas flow.

Woodchips are also assumed to have a positive effect on furnace performance by decreasing the retention time of quartz, increasing energy content in the off-gas, and increasing charge resistivity.

Particle size and shape, and the content of contaminants, are the most important properties to consider when selecting a woodchips source. Typical sizes are in the range 7.5 cm² x 1.25 cm thick to 20 cm² x 2.5 cm thick (Saadieh, 2024), or match box size (Monsen *et al.*, 2001). Fines, such as sawdust, should be avoided since they burn at the charge surface. The amount of bark is often limited since it has a higher content of contaminants.

The iron source

To produce Ferrosilicon, FeSi, iron must be added to the charge mixture. The amount of iron source in the charge mix depends on % Fe in the iron source and the iron content in the designated product, such as FeSi55 with 45% iron or FeSi75 with 25% iron. The most used iron source is steel scrap, followed by iron ore pellets and mill scale (Saadieh, 2024). In addition to price and availability, chemistry and size are important properties to consider. The chemistry of all types of iron sources varies with the steel or iron ore they originate from and must be evaluated for each case. In steel scrap, the main tramp elements are Cu, Sn, Cr, Ni and Mo, which in the most used steel scrap quality, Q4, are around 0.25–0.35%.

Iron ore pellets are available in different qualities, with blast furnace (BF) or direct reduced (DR) pellets as the most common. In addition to iron oxide, they also contain up to around 5% SiO₂, 3% Al₂O₃ and CaO, and some MgO. With a particle size of around 9–16 mm and a strength high enough for processing in a blast furnace, the iron ore pellets are well suited to be handled in a ferrosilicon plant.

When iron oxides are used, they must be reduced to Fe in the furnace, either with an excess of CO gas or with carbon, which will then increase specific energy consumption. Iron scrap reduces the need for carbon and electrical energy in the process compared to iron oxide. However, iron oxide may be easier to control regarding chemical analysis. Iron oxide pellets are normally more suitable for automatic raw material handling equipment compared to non-uniform scrap pieces.

5.4 The silicon and ferrosilicon plant

The silicon process must meet the basic requirements for the process which are described in Chapters 2 and 3. The main challenges are the need for extremely high process temperatures, energy conversion, and the thermodynamic requirement that govern the processes involved. The main components of a silicon furnace are shown in Figure 5.1 and Figure 5.12. The furnace has some basic functions that must be included in the construction. Although the size and technological level vary between furnaces, all silicon furnaces must include:

1. The furnace shaft consisting of a shell and a lining that resist the temperature and chemical load
2. Electrical supply to the furnace consisting of electrical grid, transformers, bus bar and the electrodes.
3. Equipment for handling and feeding of raw materials to the furnace.
4. Equipment for stoking and preparation of the charge mixture in the upper part of the furnace
5. Equipment for tapping silicon or ferrosilicon from the lower part of the furnace
6. Gas cleaning and energy recovery systems

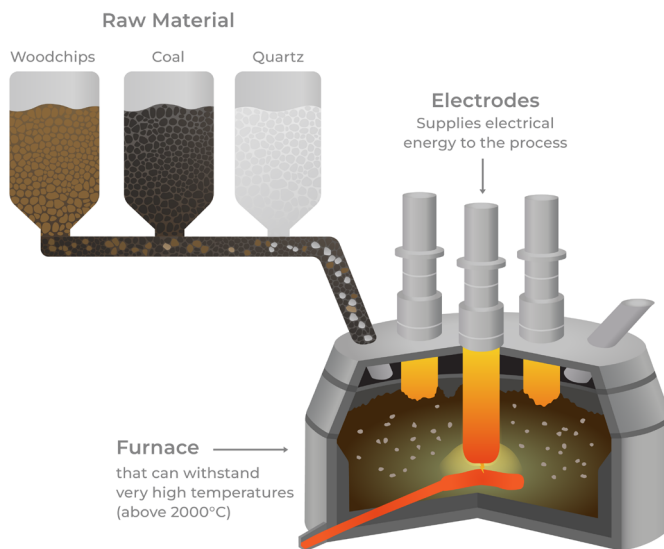


Figure 5.12 Basic requirements for Si production.

The furnace

The central part of the furnace comprises the furnace hood and the body. The furnace body consists of an outer steel shell and an inner lining that resists the temperature and chemical load required by the process. The silicon process is special because the raw materials partly perform the most demanding work on the lining. The lining is often made of oxide refractory near the outer steel shell. In the inner part of the furnace body, the lining is made of carbon material. The most severe challenge for the lining is below the electrodes and close to the tapping channels. There may be one or several tapping channels through the furnace body. The tapping channel may be made of carbon material or silicon carbide refractory.

The furnace hood is the upper part of the furnace. It has several functions: it collects the process gas; it shields the equipment from the process heat and the charging pipes; and the electrodes pass through the hood. The process gas is sucked out through pipes that pass through the hood and is transported further to the gas cleaning equipment and the chimneys. The hood may be open, but for modern, larger furnaces it is normally water-cooled and semi-closed. Semi-closed furnaces have furnace doors that open for inspection, stoking and charging. Both open and semi-closed furnaces allow abundant air to be available at the charge top. Semi-closed furnaces give a higher off-gas temperature, which is important if an energy recovery plant is connected to the furnace.

The electrical supply and the electrodes

Electrical energy is supplied to the furnace through electrodes, from the top of the furnace to the high temperature zone in the lower parts of the furnace. The energy supply system and the electrodes are a crucial part of silicon production. Good furnace performance requires good operation of the electrodes and energy supply. The electric operation is described in more detail in Chapter 6. There is a close interaction between furnace operation, energy supply and electrode operation.

Raw materials handling and feeding to the furnace

The system for handling raw materials includes transport, storage, weighing and mixing of the raw materials used in the process. Layout and technologies for the charging system are normally site dependent and vary from plant to plant and from furnace to furnace. The raw materials are transported from the supplier to the plant by railway, truck or boat. Most of the Norwegian silicon plants are located near the sea, where ships are the main transporters of the raw materials. Control of the supplier's chemical analysis is often carried out on arrival. Raw materials for up to several months of operation are stored temporarily at the plant, either outdoors, under a roof or indoors. Carbon materials can take up more moisture than quartz and are often prioritized for indoor storage in rainy areas. Many plants monitor the moisture in raw materials automatically, to better control the raw material mix.

From the storage area, the raw material is transported to the furnace. Often there are some smaller and more defined storage bins, called day bins. To obtain the right blend of raw material, predetermined tonnages of each raw material are weighed out from the silos before the raw materials are mixed and fed to the furnace. In modern furnaces, this is done by an automatic weighing system. The ratio between the different raw materials, called the material blend or charge mixture, is given to the weighing system through the control system of the furnace. To determine this ratio, the charge mixture that will give optimal furnace operation is chosen. This is adjusted based on realized furnace operation. The ratio between raw materials is one of the major challenges in furnace operation, and often the main task for the furnace metallurgist responsible for the furnace. From the weighing system, the raw material is transported to the furnace, usually on conveyor belts.

Adding new raw materials to the furnace, called charging, can be done in different ways (Andersen, 2023). In older, smaller furnaces, charging cars can be used. More often, however, the raw materials are added through charging tubes, which are connected to bins of mixed raw material and go down into the furnace through the furnace hood. The number and arrangement of charging tubes vary between furnaces. In many cases, there is a charging tube to the centre of the furnace, in addition to two or three charging tubes around each electrode, but other constellations are also seen. The raw materials are dropped from the charging tube to the charge top, giving the raw materials a thermal shock when they meet the warm charge top. Ideally, the raw materials should

be fed continuously to the furnace. The batch size and frequency of charging affect the fluctuations of moisture and volatiles in the off-gas (Andersen, 2023; Kamfjord, 2012). Different designs of charging systems have thus been developed (Myrhaug *et al.*, 2012).

Stoking and preparation of materials charge in the furnace

Condensates formed by reaction [5.2] and [5.3] are abundant in the charge above the SiC-crust, with brown condensates from reaction [5.2] being most common. They are sticky and glue the other charge materials together into a hard layer that hampers, or prevents, both the downwards flow of solid materials and the upwards flow of gases. To ensure an even flow of materials and gases, the condensate can be broken up by stoking. The most common method is to push materials at the top of the charge downwards and inwards in the furnace. This is done using an iron rod mounted on a truck (the stoking machine) that moves around the furnace on the floor outside the furnace shell. The material is stoked intermittently, normally either at fixed intervals or based on dust level in the off-gas. Alternative methods, such as a split body where the upper half of the furnace rotates, have been tried. In production of ferrosilicon, there is a lower SiO content in the gas and thus less condensate form. These furnaces, especially furnaces producing ferrosilicon with lower Si contents, are often operated without stoking.

Stoking requires access to the charge top from outside the furnace. This can be either via an open furnace or, as is most common today, through doors or ports in the furnace sides that are opened when stoking is required. Both alternatives allow an inflow of air that reacts with SiO to SiO₂ and with CO to CO₂, resulting in a high CO₂/CO ratio in the off gas.

Tapping of liquid silicon or ferrosilicon

Produced silicon or ferrosilicon is tapped out either intermittently, but in most cases it is tapped continuously through tap holes in the lower part of the furnace. The furnace has around 5–7 tapholes, constructed with a dedicated lining and front. The tapping channel is opened by a tapping tool. Several kinds of tapping tool are used, such as a steel rod for poking, oxygen lances, electrical graphite bars for burning, or other mechanized or manual equip-

ment. Fully automated tapping robots are being developed and are installed at many furnaces. Tapped metal has a temperature of around 1900 °C when it leaves the furnace. It might be accompanied by a jet of tapping gas (Andersen *et al.*, 2022; Ksiazek *et al.*, 2018). Each taphole is used for around 10 days, varying from furnace to furnace. It is then plugged with ramming paste, and a new taphole is opened. Silicon and ferrosilicon furnaces usually rotate, with a speed of around 25 days for one rotation, with a lot of variation from case to case. Some furnaces oscillate instead. The position for the tap hole will thus change, making it easier to use tap holes distributed around the furnace.

Good tapping, and thus good drainage of the metal, is vital for good furnace operation and to avoid operational problems. This is also described in Chapter 8. Metal produced in the cavity and below the electrodes has to be drained out through the tapping channels in the furnace and the lining to the tap hole (Tangstad *et al.*, 2021). Problems with drainage may lead to higher pressure in the cavity, loss of SiO-gas and lower Si-yield. It will also give a risk of gas jets from the taphole (Kadkhodabeigi, 2011). The taphole, tapping area and equipment are exposed to high temperatures and high mechanical and chemical stress. It is thus a part of the furnace that is difficult to automate and that requires much maintenance.

The liquid silicon or ferrosilicon is first tapped into ladles. Its composition can be adjusted by alloying or refining in the transport ladle as described in Chapter 10. Liquid Si or FeSi is then solidified by casting. Several ways of casting silicon and ferrosilicon, described in Chapter 11, are in use today.

Gas treatment and energy recovery

Silicon and ferrosilicon production are energy intensive processes. A large part, around 1/3 (Kamfjord, 2012), of the supplied energy will, as discussed in Chapter 7, go into the off-gas. The energy in the off-gas may, and is at many modern furnaces recovered as high temperature water or as steam, which can be further converted to electrical energy. SiO in the off-gas is burned with oxygen to silica fume, which consists of nano particles of SiO₂. The silica fume is normally removed from the off-gas in baghouse filters and is a valuable by-product. It can be used for different purposes, i.e. to improve concrete. Its value depends on the content of minor elements. Microsilica is one of the trade names used for silica fume.

The energy balance for the process presented in Chapter 7 assumes burning of the CO gas, the SiO gas and volatiles. The burning, and the temperature control with cooling air, results in a large amount of waste gas containing condensed silica fume. In theory, the furnaces could be closed, with no combustion of CO gas and volatiles. This presents several challenges and, so far, there have been only experimental trials of closed silicon furnaces and FeSi furnaces with high silicon content (Arnesen and Bjordal, 1980).

5.5 Furnace operation and control

Economy and sustainability in silicon production is dependent on the operation results. The main process parameters are furnace load (kW), silicon yield (%), specific energy consumption (kWh/ton) and CO₂ emissions (kg/ton alloy). Other parameters, such as product quality, emissions and operation time (%), are also important. Achieving and maintaining an economic and sustainable production process requires good process control. To achieve this, one must have a good combination of

- Process measurements
- Control system
- Metallurgical competence about the actual process

Metallurgical competence is the basis for good furnace operation and is the focus of the current book. Part of this competence can be systematized into various process models, as a help to the metallurgists and operators in making their decisions.

Process measurements provide data required to evaluate process performance and the effects of changes in the operational strategy, parameters or raw materials. They are used by the metallurgists and furnace operators and are also input into process models. Process measurements are also needed and are mostly used as input to the control system. Process measurements also include process surveillance by standard and infra-red camera.

Part of the furnace operation is automatic, and is done by the control system. The control is based on process measurements combined with set points given by those responsible for the furnace. This is especially useful for

electrode movements, since the electric parameters change very fast. It is also standard at most furnaces for several other operations, such as weighing and charging system and electrode slipping.

Process measurements

Process measurements are needed as input to the control system and to provide information for the metallurgist and furnace operators when deciding on operational and raw material parameters. The type of process measurements and the methodology is often plant or furnace specific. New methods are continuously developed. Details regarding process measurements will thus not be further described here.

Control system

Automatic operation requires a control system. To work well, this needs to be designed with control algorithms suited for the process it controls, to have input from reliable process measurements, and to use well-founded set-points chosen by the metallurgists. There is a development towards use of digital twins and artificial intelligence (AI) to support the control system and choice of set points.

The process parameters in silicon production have large variation in time delay. Electrical parameters have response within seconds, while some of the metallurgical parameters may need weeks or months to adjust. Build-up of carbon materials and distribution of reaction zones in the furnace are examples of these. The interaction between the electrical and metallurgical subsystem in the process is indicated on Figure 5.13. The electrical system may have a closed loop control due to the short time constants and the good signals from the process. Parameters in the electrical system, such as electrode position and slipping, voltage, current and load control, or transformer tap position, are in most furnaces computer controlled. The metallurgical system has longer time constants, more variation in time delay and less direct readings of main parameters from the process, and is normally partly computer controlled and partly operated by the metallurgist and the furnace operator.

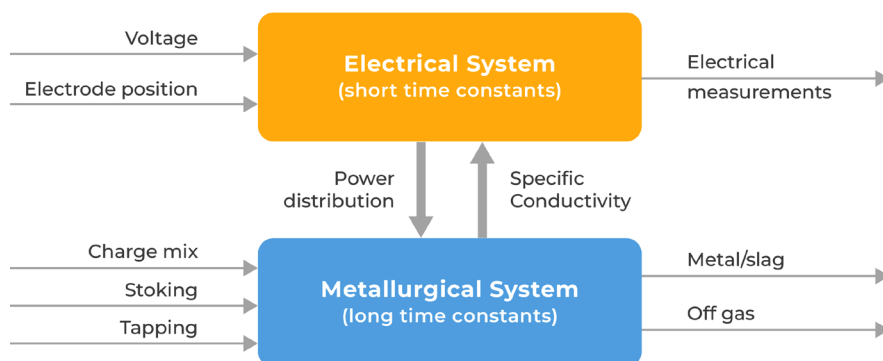


Figure 5.13 *The principal interaction between the metallurgical and the electrical system in the silicon process.*

Metallurgical competence

Metallurgical competence in the Si process is the key factor for good furnace operation. This is the focus of this book. Process competence is needed to optimize the raw material mixture, choose operational strategies, and select the set points for the various control systems. The development and implementation of new control systems require in-depth knowledge of the process.

Such competence can be systemized into process models as tools and aids for controlling and optimizing the process. Several process models have been developed and used over the years. Often, each plant or company uses its own in-house model. Fundamental theoretical and practical knowledge about the process is needed both to use and to develop models and control systems, and to know when the models should, or should not, be used.

5.6 Process models

Process models are decision-support tools in which metallurgical competence, and details about reactions and physical phenomena in the furnace, are systemized into an overall understanding of the process. The interdependent physical phenomena in a silicon furnace – including chemical reactions,

thermodynamics, kinetics, material and gas flow, electrical currents, and energy distribution, all relying on varying properties of different raw materials – can then be handled more easily. A model can cover a selected part of the Si/FeSi process, such as tapping, the electric arc, or the off-gas system. However, an overall model of the whole process is often the tool most needed by the furnace metallurgist, and this is what is described here. For a complex system such as the silicon furnace process, all models require a considerable number of assumptions and simplifications. The key is to capture the main effects of actual variables, within the variations expected in an industrial furnace, with reasonable requirements for the accuracy of input parameters and reasonable simulation time. A process model will therefore not simulate or explain all phenomena that take place in a silicon furnace, nor predict what is happening under completely new conditions; rather, it indicates what might happen when conditions or raw materials are changed. Process models are also a good tool for the metallurgist to investigate which choice of raw materials or conditions will give the best furnace performance when several alternatives are available.

The Si process was developed empirically. Modelling started, as described in Schei (1998), with various qualitative models in the 1970s, and continued with furnace models in the 1990s (Schei *et al.*, 1998). With the development of more advanced computer technology with higher capacity, and the development of AI tools, there has been a move towards more complex and more advanced models, such as transient models (Darmana *et al.*, 2012; Olsen *et al.*, 2022) and mathematical modelling (Sloman, 2018). The development of Digital Twins gives a closer connection between the models and operation (Linnestad *et al.*, 2022). Many producers develop their own process models, incorporating their own process competence and experience from their own operation. These are often confidential. Examples of producer models are the Elkem models, Si mod and FeSi mod (Sloman, 2018). These Elkem models are a further development of earlier published work. The concept and assumptions behind the models give insight into different approaches and challenges in the modelling of Si and FeSi furnaces.

Background and concept for Elkem process models

Elkem has developed two models of the silicon process:

- A stoichiometric model
A very simple steady state model that combines equilibrium and kinetic considerations with material and energy balances. The model, which contains only arithmetic calculations, is implemented in Microsoft Excel, and a case can be calculated in a few seconds on a personal computer.
- A unidimensional dynamic model
A model with simple rate laws for the chemical reactions. The material and heat balances are formulated as differential equations, which are integrated numerically by a suitable time stepping algorithm. Calculation of a case can take minutes to hours on a large personal computer.

The models are described in several publications. Schei and Larsen have given the metallurgical background for the stoichiometric model (Schei and Larsen, 1982). Schei and Halvorsen have developed the numerical calculation and discussed the silicon process based on calculated examples (Schei and Halvorsen, 1991). Halvorsen *et al.* (1993) have described the dynamic model from a metallurgical point of view, while Halvorsen *et al.* (1991) and Halvorsen (1994) have given a thorough discussion of the mathematical problems. Halvorsen has presented the use of both models in the education of process metallurgists in Elkem (Halvorsen, 1995).

The stoichiometric model

The model sees the silicon process as a combination of simple reactions between stoichiometric compounds of the main elements Si, O and C. It ignores the presence of foreign elements that always will be present in a real process. The simple model, also described in Chapter 3, is based on furnace observations and knowledge of the chemistry of the system. In this model, the gas from the inner zone of the furnace has a high content of SiO, and this SiO has to be recovered in the outer zone of the furnace if the silicon yield of the process is to be high. The recovery mechanism used was the reaction



In addition, it was indicated that the condensation mechanism



could be an important second main recovery mechanism. The other condensation reactions between SiO and CO seem to be so slow that they can be ignored in a rapid calculation. The recovery mechanisms are the core of the stoichiometric model, which is sketched schematically in Figure 5.14.

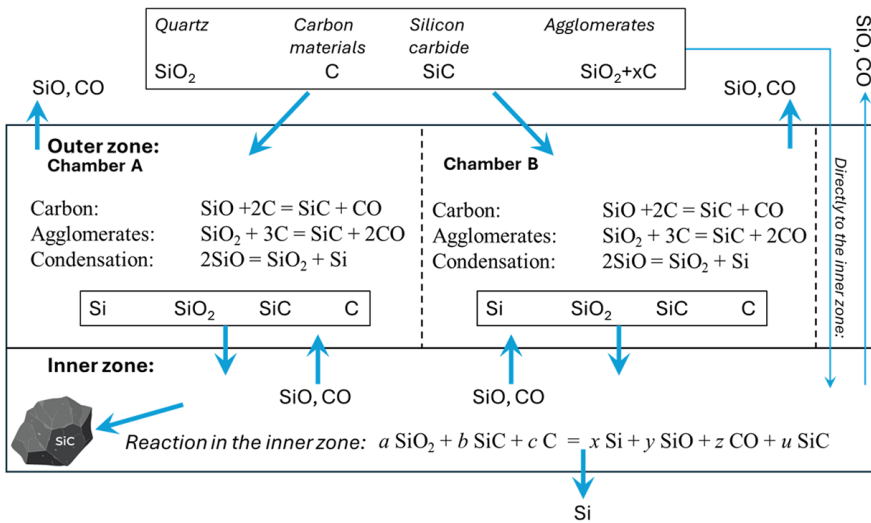
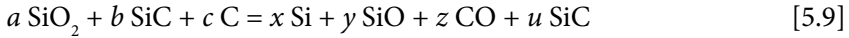


Figure 5.14 Survey of the stoichiometric model with the material flows.

The furnace is split into an inner zone, where SiO_2 and SiC react, and an outer zone, where the SiO in the gas from the inner zone is recovered. The raw materials are charged into the outer zone, where they interact with the outgoing gas in counter-current. The outer zone is split into two chambers to permit simulation of uneven gas distribution through the charge. The charge and gas can bypass the outer zone.

The inner zone

In the inner zone of the furnace, SiO_2 , SiC and C disappear, while Si and gas SiO-CO are produced. Under some conditions, solid SiC is deposited in the lower part of the furnace. These observations are expressed by the inner zone reaction:



This must be seen as a non-equilibrium overall reaction, since there are more phases than allowed by the phase rule for the given conditions. Equilibrium silicon production at fixed pressure is possible in the inner zone only for the condensed phases SiO_2 , SiC and Si . The equilibrium gas is determined by the reaction:



$$\frac{p_{\text{CO}}}{p_{\text{SiO}}} = K_{5.7} \quad [5.10]$$

The equilibrium fraction of SiO in the gas is given by:

$$s = \frac{p_{\text{SiO}}}{p_{\text{SiO}} + p_{\text{CO}}} = \frac{p_{\text{SiO}}}{p_{\text{SiO}} + K_{5.7}} = \frac{1}{1 + K_{5.7}} \quad [5.11]$$

Temperature and gas composition are completely determined with $s \approx 0.67$ at 1811°C . As shown in Chapter 3, this SiO content will give a silicon recovery of 33 per cent. However, the best obtained process recoveries are above 90 per cent, and the observed reaction temperature is about 2000°C . The real reaction therefore runs far from equilibrium.

Experience suggests that the slowest step is the heat-consuming break-up of SiO_2 . When energy is added, the temperature rises and, consequently, the reaction rate increases until energy consumption and energy addition balance in a steady state. In this non-equilibrium reaction, the SiO content s of the gas in the inner zone is determined by the reaction kinetics. Thus, s is variable, however, in the stoichiometric model it is *assumed* to be constant for a certain combination of raw materials and operating conditions. As a first approximation, we assume that Reaction [5.7] is relatively rapid and that s

can be estimated from the temperature in Figure 5.15. The crater temperature 2000°C corresponds to an s value slightly below 0.50. This value can therefore be taken as a rough indication of the value of s .

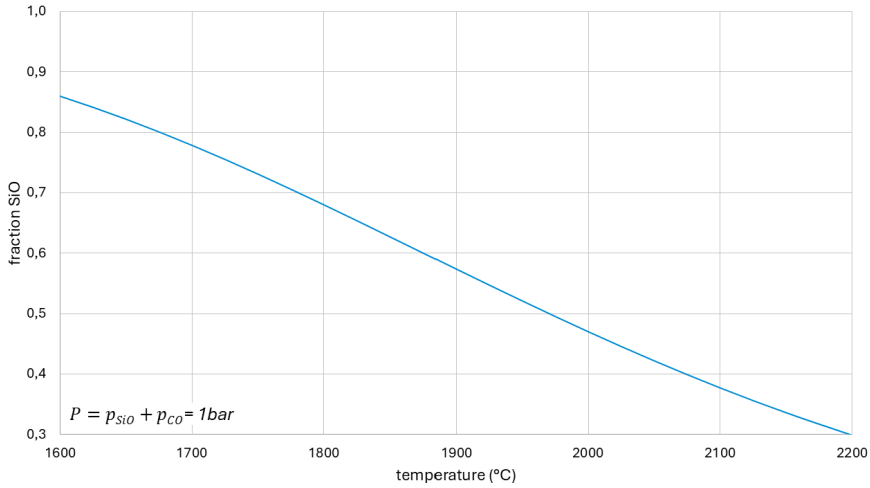


Figure 5.15 The SiO content of the gas in equilibrium with the condensed phases Si and SiC calculated.

The aim of the model is to describe steady-state operation, and it is assumed that Si is always present. Reaction [5.9] will then proceed as long as SiO_2 is present (x will be negative if Si is consumed). The flows a , b and c to the inner zone in Reaction [5.9] are assumed known, and the material balances for Si, C and O give three equations for the unknown coefficients x , y , z and u . Additional information can be taken from the general definition of s , and from the observation that the ratio between the gas pressures must be equal to the ratio between the gas flows. If SiC is present,

$$s = \frac{p_{\text{SiO}}}{p_{\text{SiO}} + p_{\text{CO}}} = \frac{y}{y + z} \quad [5.12]$$

The element balances are

$$\text{Si:} \quad a + b = x + y + u \quad [5.13]$$

$$\text{C:} \quad b + c = z + u \quad [5.14]$$

$$\text{O:} \quad 2 a = y + z \quad [5.15]$$

The solutions are

$$x = a (3 - 4 s) - c \quad [5.16]$$

$$y = 2 a s \quad [5.17]$$

$$z = 2 a (1 - s) \quad [5.18]$$

$$u = b + c - 2 a (1 - s) \quad [5.19]$$

These solutions apply when SiC is in excess, that is, for $u > 0$. In this case, the gas composition is controlled by the parameter s .

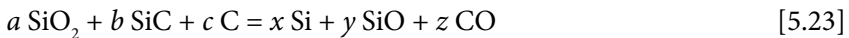
$$u = b + c - 2 a (1 - s) > 0 \quad [5.20]$$

$$\frac{b + c}{2a} > 1 - s \quad \text{Gas composition is controlled by } s \quad [5.21]$$

When $u \leq 0$, this condition is not fulfilled, and the gas composition is instead controlled by the stoichiometry of the materials going into the inner zone. That is,

$$\frac{b + c}{2a} \leq 1 - s \quad \text{Gas composition is controlled by the stoichiometry} \quad [5.22]$$

Reaction [5.9] then changes to



and the element balance gives the complete solution:

$$x = -a + 2b + c \quad [5.24]$$

$$y = 2a - b - c \quad [5.25]$$

$$z = b + c \quad [5.26]$$

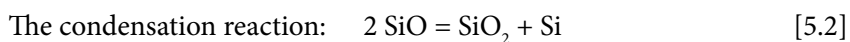
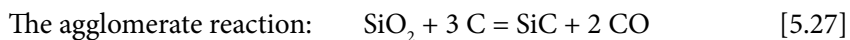
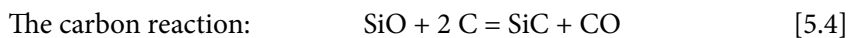
Therefore, to determine the coefficients of the reaction of the inner zone, one can use the inequalities [5.21] or [5.22] to decide which set of coefficients applies: [5.16]–[5.19] or [5.24]–[5.26].

The outer zone

The reaction in the outer chambers A and B recovers heat and SiO from the gas of the inner zone. The operation is assumed to run in a repeated cycle:

- The chamber is filled with cold charge materials
- The furnace is run until all the SiO₂ of the preceding filling is completely consumed in the inner zone
- The remaining materials in the chambers are stoked into the inner zone.

In Chapter 2 it was shown that the rate of the reaction between SiO₂ and C depends strongly on the particle size. In industrial furnace operation, the size is generally about one centimetre for carbon particles and several centimetres for quartz particles. For such particles, the reaction between SiO₂ and C will be very slow at the temperatures in the outer zone. However, if the materials are finely crushed and agglomerated, the rate will increase strongly. This option is included in the model, therefore, three reactions are assumed to be important in the outer zone:



The reactions in a chamber, and the flows into and from it, are sketched in Figure 5.16.

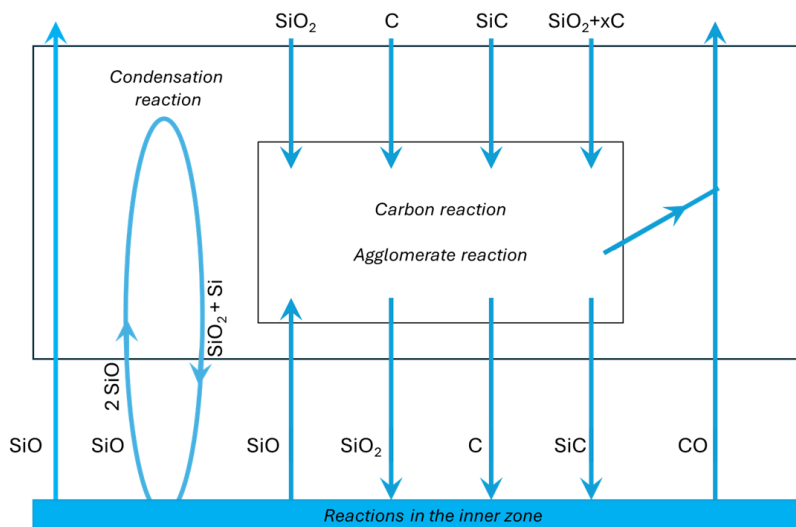


Figure 5.16 The reaction in chamber A or B in the outer zone and material flows in and out of it.

From practical experience, it is known that carbon materials often do not react completely. We therefore define a *reactivity number* r , which gives the fraction of the carbon that is available for reaction. Similarly, we define two reactivity numbers for the carbon in the agglomerates. First, there is a reactivity number for the direct reaction between SiO_2 and C in the agglomerate. Second, there is a reactivity number for any free carbon left after the SiO_2 has been completely consumed.

SiO from the inner zone is recovered either by reaction with carbon or by condensation. Condensation is strongly heat-producing, and the heat is absorbed either by raising the temperature of the ingoing raw materials or by heat-consuming reactions in the zone. The agglomerate reaction can absorb large quantities of heat. The amount of SiO that can be recovered is determined by the heat capacity (for heating and reaction) of the charge and by the carbon available.

When a sufficient amount of SiO is available, it is assumed that all the available C and the agglomerate react. SiO then condenses until the charge is heated to the condensation temperature. If the amount of SiO is insufficient, all the SiO reacts, and only a fraction of the charge is heated to the reaction temperature and reacts according to Reactions [5.4] and [5.27]. In that case, the reactivity numbers apply only to the heated fraction of the charge.

Calculation

The model has the following parameters that must have specified values:

- Amounts of SiO₂, C, SiC, agglomerate, content of SiO₂ and C in agglomerate.
- Distribution of the raw materials: Chamber A, Chamber B, directly into the inner zone.
- Distribution of the gas from the inner zone: Chamber A, Chamber B, directly out of the furnace.
- Reactivity number of the carbon in carbon materials.
- Reactivity number of the agglomerates.
- Thermal efficiency of the furnace.
- Temperature of the cold CO (CO leaving the furnace before the charge is heated to the condensation temperature).

As shown in the description of the inner zone, the reaction is easily calculated if the flow of materials entering the zone is known. The reaction in the outer zone is governed by a set of assumptions: the reaction between SiO and C runs until the available C is consumed; any remaining SiO is allowed to condense until the charge reaches the condensation temperature; and any excess free C goes into the inner zone. The reactions can be calculated from these assumptions and the heat balance when the material flows into the zone are known. The overall system is calculated by choosing arbitrary initial values for the flows into the inner zone and then iterating between the inner and outer zone until the reactions are consistent.

The model can be implemented on an Excel spreadsheet. The iteration typically converges within a few seconds. With known reactions, the energy consumption can be calculated.

Calculated examples

The use of the model will be demonstrated by some calculated examples. These examples show many properties of the silicon process, and together they provide a rough understanding of the process as background for the practical operation of a furnace. In the examples, the charge and the operational parameters are varied around a standard set that is shown in Table 5.2. The standard values are chosen to give reasonable results for all the steps in the calculation. However, it should be remembered that the calculations are examples based on the values of several parameters, and the conclusions should be interpreted with some scepticism concerning general applicability.

Table 5.2 *Standard values of the charge and the parameters used in the calculated examples from the stoichiometric model.*

Charge	SiO ₂	C	SiC	SiO ₂ + x C
Composition in moles	1.00	1.85	0.00	0.00
Chamber A (fraction)	0.50	0.50		0.50
Chamber B (fraction)	0.50	0.50		0.50
Reactivity carbon				
Chamber A		0.72		0.90 (0.80) ¹⁾
Chamber B		0.72		0.90 (0.80) ¹⁾
Operation		Operation		
Gas distribution		Heat added in charge		
Chamber A (fraction)	0.5	Chamber A, kW		0.00
Chamber B (fraction)	0.5	Chamber B, kW		0.00
Cold CO		Aggl., x in SiO ₂ + x C		1.9
Chamber A (K)	298	s Minimum SiO inner zone		0.45
Chamber B (K)	298	Thermal efficiency		1.20

- 1) The first value applies to the reaction between SiO₂ and C, while the value in the parentheses applies to the remaining free carbon after the direct reaction SiO₂ + x C.

Example 1 – Carbon content of the charge

The carbon content of the charge is one of the most important parameters of furnace operation, and the metallurgist can easily vary it. In industrial practice, the carbon content is chosen based on raw material analysis and former experience, and it is then corrected during operation according to furnace behavior. It can be described by the parameter x in $\text{SiO}_2 + x \text{ C}$ (or by an analogous definition for SiC in the charge). The influence of the carbon content in the model is illustrated in Figure 5.17, where the success of the operation is characterized by the silicon recovery.

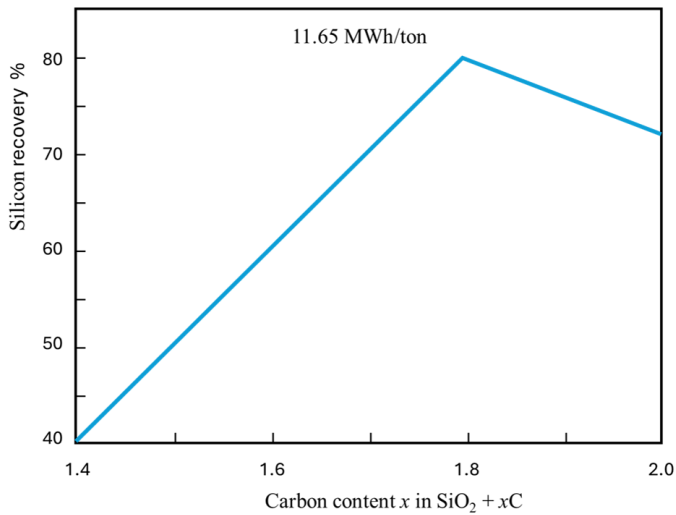
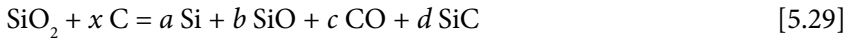


Figure 5.17 The silicon recovery as a function of the carbon content of the charge calculated by the stoichiometric model.

With the chosen parameters, the model gives a silicon recovery of about 80 per cent at an optimum value $x_{\text{opt}} \approx 1.8$. The recovery then drops strongly on either side of this maximum. A study of the details of the calculation shows that a carbon content lower than the optimum corresponds to an inner-zone reaction:



The SiO content of the gas will then be higher than the value corresponding to the parameter s . By contrast, a carbon content higher than x_{opt} gives a reaction of the type:



The optimum carbon content depends on the values of the parameters in the calculation. The terms surplus or deficit of carbon should therefore refer to this optimum. If the furnace operates at the optimum carbon content, both an increase and a decrease will reduce the silicon recovery. Even with a surplus of carbon, there will be a silicon loss as SiO. However, if the operator tries to counteract this loss by adding more carbon, SiC will be deposited at the bottom of the furnace, and the overall silicon recovery will decrease.

Silicon lost as SiO reacts with O_2 above the charge and is captured as microsilica in the off-gas system. Silicon deposited as SiC at the furnace bottom will eventually block the operation, and large deposits must be avoided. Therefore, some metallurgists prefer to operate safely with a low carbon content, but at the price of reduced silicon recovery. The ability to run the furnace close to the optimum carbon content is a goal for furnace instrumentation and for the training of operators and metallurgists for silicon production.

Example 2 – Uneven gas distribution

In a unidimensional model, we assume that the flow of mass and the reactions are evenly distributed across the cross section of the furnace. This is evidently a rather crude assumption, as can be seen from the uneven distribution of the flames on the top of the furnace. The importance of this unevenness can be estimated from the model. An example is shown in Figure 5.18. The unevenness is characterized by a ratio:

$$\text{Gas distribution ratio} = \frac{\text{Percentage of gas through chamber A}}{\text{Percentage of gas through chamber B}} \quad [5.30]$$

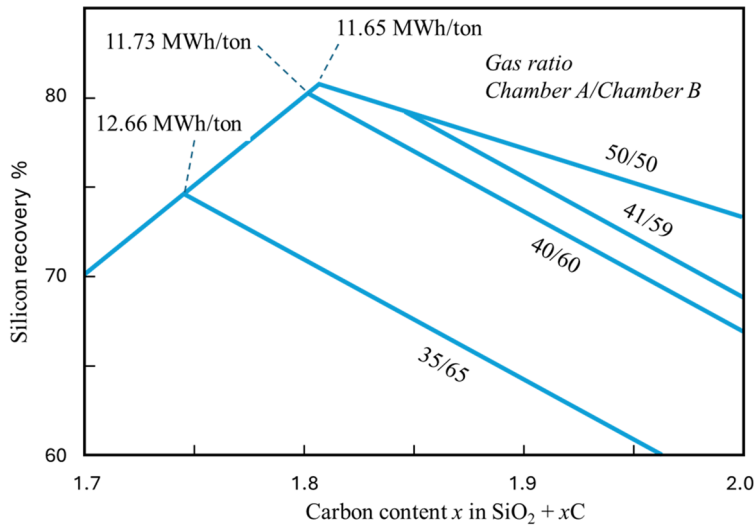


Figure 5.18 The silicon recovery as a function of the carbon content of the charge calculated by the stoichiometric model for various gas distribution ratios. The silicon recovery has an optimum of 80.7% at $x = 1.807$.

For the even gas distribution ratio 50/50, the silicon recovery as a function of the carbon content, goes through a maximum, as demonstrated above. With a moderately uneven distribution, the optimum silicon recovery is unchanged. However, on the right-hand side of the figure there is a range in which the Si recovery decreases more rapidly with increasing C content than it does for the even gas distribution. As the unevenness increases, this range of lowered silicon recovery covers an increasingly large part of the carbon distribution range, and at a certain value it reaches the optimum carbon content. With a further increase in unevenness, the obtainable silicon recovery decreases. In the model, the consequences of an uneven distribution are caused by incomplete counter-current flow between gas out and materials in. With excess gas through one chamber, the SiO-binding capacity of that chamber may be exceeded, while a lack of SiO in the other chamber may allow free C to enter the inner zone. The result is increased silicon loss, unless there is an excess of SiO-binding capacity in the system. Because of such an excess, the

lowering of the optimum silicon recovery does not start as soon as the gas distribution becomes uneven.

Uneven distribution of the raw materials will have a similar effect. Such uneven distribution may occur because of segregation in the charge. In the raw materials, the maximum lump size is about 100 mm for quartz and about 20 mm for carbon materials. This large variation in particle size may cause serious segregation in the charge materials during transport through the feeding system. The resulting unevenness in material distribution may also lead to uneven gas resistance and, consequently, uneven gas distribution. In special situations, uneven gas and charge distribution can counteract each other and give a fairly high silicon recovery.

Example 3 – Reactivity of carbon

The carbon materials will normally not react completely with SiO in the outer reaction zone, even when there is sufficient SiO available. They consist of particles up to 20 mm, where the reaction starts at the surface and forms a layer of porous SiC between the gas and the free carbon, as discussed in Chapter 2. The SiO has to diffuse through this layer to reach the carbon, and the reaction will slow down as the layer thickens. Normally, some free C will be left in the interior of the carbon particles when they are transferred to the inner zone. This behavior is simulated in the model by the reactivity number r , which is simply the fraction of the original carbon that will react in the outer zone if sufficient SiO is available. The influence of the reactivity number r is shown in Figure 5.19, where the silicon recovery is calculated as a function of r for two values of the parameter s . The reactivity number of the carbon can be controlled by the selection of raw materials. For a given carbon material, the reactivity number will increase with decreasing particle size.

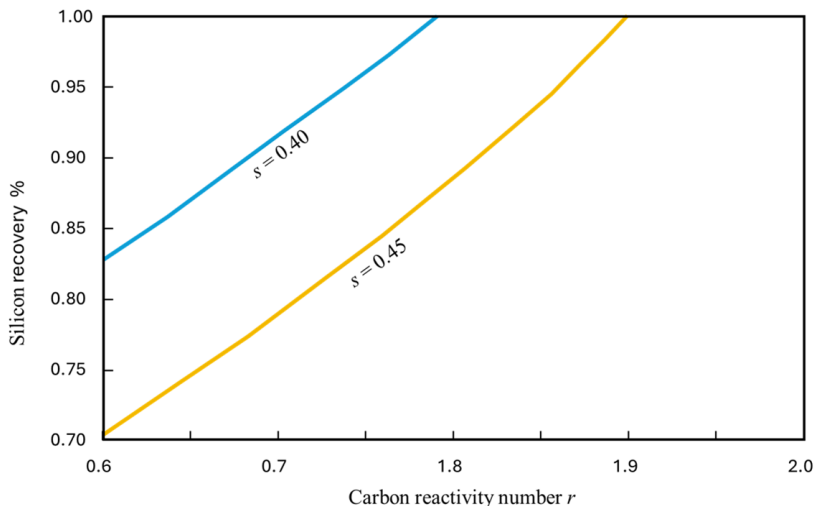


Figure 5.19 The silicon recovery as a function of the carbon content of the charge calculated by the stoichiometric model for various values of the parameters r and s . At equilibrium in the inner zone $s = 0.45$ corresponds to 2036°C and $s = 0.40$ to 2091°C according to Figure 5.15.

Figure 5.19 also shows the influence of the parameter s . As a first approximation, it has been identified with the equilibrium for Reaction [5.7] between SiO and SiC. Figure 5.15 shows that $s = 0.45$ corresponds to an inner zone temperature of about 2040°C, and $s = 0.40$ to about 2090°C. An increase in the inner zone temperature improves the silicon recovery strongly. However, the temperature cannot be regulated directly. Normally, the furnace is run with the maximum electric load, and the temperature is then determined by the rate of the heat-consuming reactions and by the addition of charge.

This example shows the advantages of a high temperature in the inner zone. There are, however, some drawbacks to a high temperature. The solubility of C will increase, and this C will precipitate as SiC when the alloy cools. Such precipitation may block the fissures through which the melt flows through the bottom to the taphole. A high temperature also increases the evaporation of silicon as Si(g). The Si(g) may react with C in a reversal of the reaction



and deposit lumps of crystalline SiC in places where the heat of reaction can be given off.

Example 4 – Use of agglomerated charge

In a lump charge, there is negligible reaction between SiO_2 and C in the outer reaction zone, and the C can react mainly with the SiO from the inner reaction zone by Reaction [5.3]. The extent of this reaction is restricted by the amount of C available. In addition, some SiO is bound by the condensation Reaction [5.2]. However, this reaction is strongly heat-producing, and it will heat the charge to a temperature at which the SiO will pass through without condensing. The amount of SiO that can condense will increase if heat is removed. It has been suggested that the charge could be cooled by spraying water on the top of the charge. This cooling can, in principle, increase the condensation, but it will also decrease the thermal efficiency of the furnace, since it is difficult to find a useful application of the water vapour in the gas. The cooling will be more beneficial if the removed heat is used in the furnace process, for example by the reaction



in the outer zone. This strongly heat-consuming reaction can run below the condensation temperature of SiO if finely ground SiO_2 and C are mixed and agglomerated in intimate contact. An example of calculated results is shown in Figure 5.20. For the parameters chosen, the silicon recovery can increase from about 80 per cent to 100 per cent. The stoichiometric model shows no theoretical limit to a 100 per cent silicon recovery. However, the price of the increased silicon recovery is a high load of condensate that may obstruct the gas flow and make stoking difficult and inefficient. No really successful industrial applications have been reported. Chapter 9 gives a further discussion of this option.

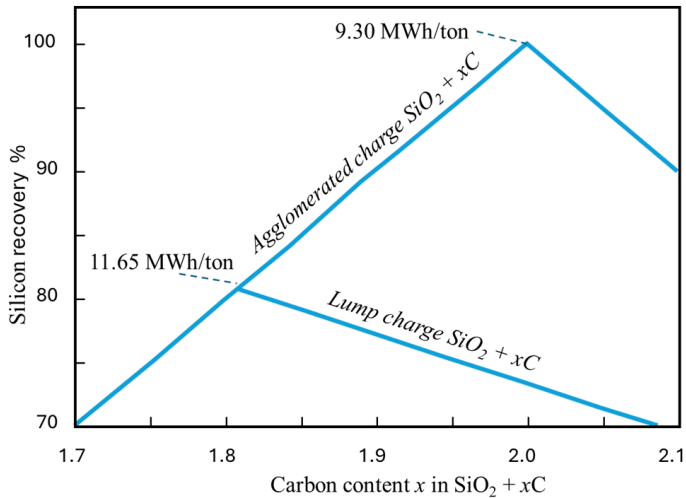


Figure 5.20 The silicon recovery as a function of the carbon content of the charge calculated by the stoichiometric model for agglomerated and lump charge.

The dynamic model

The stoichiometric model does not take into account the dynamic interaction between reaction kinetics, heat transfer, mass transfer, and electrical conduction. Therefore a more advanced model has been developed for the metallurgical behavior in the upper part of the furnace (Halvorsen *et al.*, 1993). The interaction between electric conductance and metallurgy is still neglected, and the electrode is treated only as a constant heat source. The furnace is split into two main parts (Figure 5.21): The shaft and the hearth. The shaft is split into an arbitrary number of segments, while the hearth is treated as a unity without any inner structure. Only the species SiO_2 , C, SiC, Si, CO and SiO are considered. The model is one-dimensional and describes the height variations in the active part of the furnace for a 1 m^2 cross section area. The model calculates reaction rates, gas compositions and transport of material and energy between the segments. A brief discussion of the metallurgical content of the model will be given in the following. The mathematical formulation and solution are described by Halvorsen *et al.*, and Halvorsen (Halvorsen, 1994; Halvorsen *et al.*, 1993, 1991).

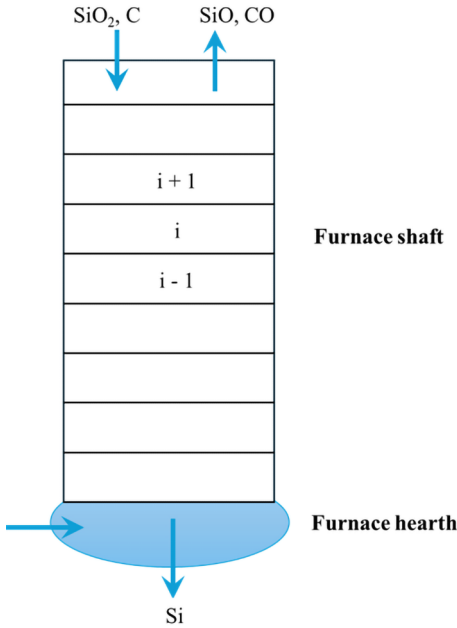


Figure 5.21 Furnace hearth and shaft in the dynamic Elkem model of the silicon process. The shaft is partitioned into an arbitrary number of segments, while the hearth is treated as a unit.

The reaction rate laws are based on deviation from equilibrium. For each reaction, a driving force is defined. As an example, the rate law for the reaction



is formulated as

$$R_{5.4} = a_{5.4} c_c \Delta p_{5.4} \exp\left(-\frac{e_{5.4}}{RT}\right) \quad [5.31]$$

where

- $R_{5.4}$ is the reaction rate (moles $\text{s}^{-1} \text{m}^{-3}$) of Reaction [5.4]
- $A_{5.4}$ is the rate constant
- c_c is the local concentration of carbon (moles m^{-3})
- $\Delta p_{5.4}$ is the deviation from equilibrium pressure
- $E_{5.4}$ is the activation energy in the Arrhenius rate equation (kJ $\text{mole}^{-1} \text{K}^{-1}$)
- R is the molar gas constant (kJ mole^{-1})
- T is the local temperature (K).

Reaction [5.4] causes a certain number of moles of SiO to be consumed, while the same number of moles of CO is produced. This property has been embedded in the model by defining the deviation from equilibrium as

$$\frac{p_{\text{CO}} + \Delta p_{5.4}}{p_{\text{SiO}} - \Delta p_{5.4}} = K_{5.4} \quad [5.32]$$

where

- p_{SiO} is the local SiO pressure
- p_{CO} is the local CO pressure
- $K_{5.4}$ is the equilibrium constant for Reaction [5.4] at the local temperature.

The reaction rates for the remaining reactions are defined analogously. In the hearth reactions, concentrations are replaced by the amount of material per m² cross-sectional area, since no height is defined for the hearth.

The reaction rates are proportional to the amount of the reactants only within certain limits. For instance, the reaction rate of the silicon-producing Reaction [5.7] is not likely to increase if more SiC is added to a hearth where there is already a large amount of SiC present. This is included in the model by specifying a maximum amount of hearth SiC that is available.

The kinetic parameters, such as $a_{5.4}$ and $E_{5.4}$ in Equation [5.31], should ideally be determined experimentally, and the form of the rate equation should apply to the critical step of the corresponding overall reaction. However, such data are not available. Therefore, the kinetic constants are defined for the overall reactions, and the values are determined by adjustment until the model predicts the furnace behavior reasonably well.

The dynamic model can be operated in two modes:

- The continuous feed mode
- The stoking cycles mode.

In the continuous feed mode, the height of the furnace is kept constant, and voids created by reactions are filled immediately from above. The shaft is refilled continuously with new charge to maintain the top level. In the stoking cycles mode, the top of the shaft is kept at a constant position. When voids

are created, the material content of the shaft shrinks, and the shaft–hearth interface moves towards the top. The furnace is stoked when predetermined conditions are fulfilled. During stoking, the content is pushed down until the shaft–hearth interface is in the original position, the upper part of the shaft is filled with new charge, and a new cycle starts.

Comparison with the stoichiometric model

Two computational series were compared. In one series, it was assumed that some of the SiC in the hearth was unavailable for reaction, while in the other series all the SiC was available. The silicon recovery from several runs in each series was plotted as a function of the molar ratio C/SiO_2 in Figure 5.22. The points in each series fell on two straight lines crossing at an optimum, as predicted by the stoichiometric model (Figure 5.17). For quantitative comparison, it is necessary to find parameters that are equivalent for the stoichiometric and dynamic models.

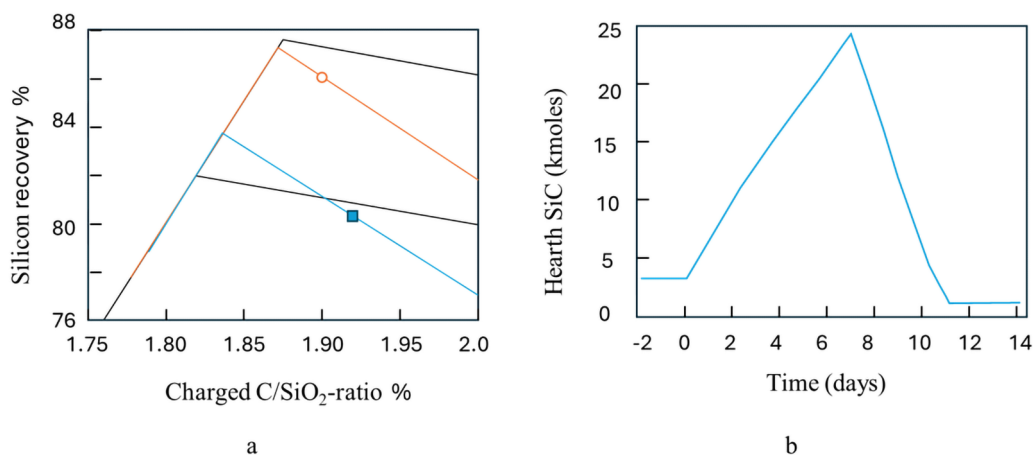


Figure 5.22 Comparison of the dynamic and the stoichiometric models.

Solid lines – the stoichiometric model.

Open circles – dynamic model without restricted availability of SiC in the hearth.

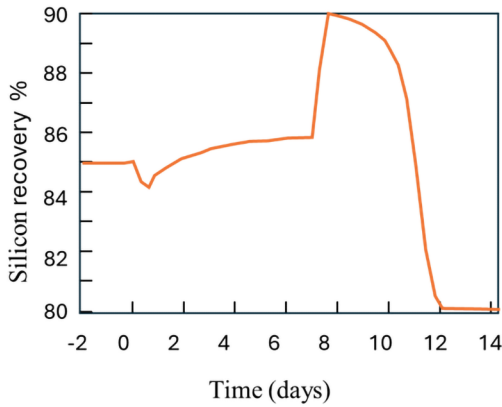
Filled squares – dynamic model with restricted availability of SiC in the hearth.

First, it was assumed that the hearth and shaft of the dynamic model correspond to the inner and the outer zone, respectively, of the stoichiometric model. The value of s was set equal to the SiO content calculated for the hearth in the dynamic model ($s = 0.564$ and 0.549 , respectively, for runs with and without restrictions on the SiC availability in the hearth). The fraction r of the carbon reacting in the outer zone was then fitted so that the stoichiometric model gave the same Si recovery as the dynamic model with SiC restrictions in the hearth for the C/SiO₂ ratio 1.90. The result is shown in Figure 5.22a, but the two models deviate significantly. As an alternative comparison, both s and r were fitted to the series with restricted SiC availability ($s = 0.445$, $r = 0.592$). Then only the s value was changed (to 0.4339) to account for the difference between the two series. The results of the comparison are shown in Figure 5.22b. With these parameters, the dynamic and the stoichiometric models predict the same results.

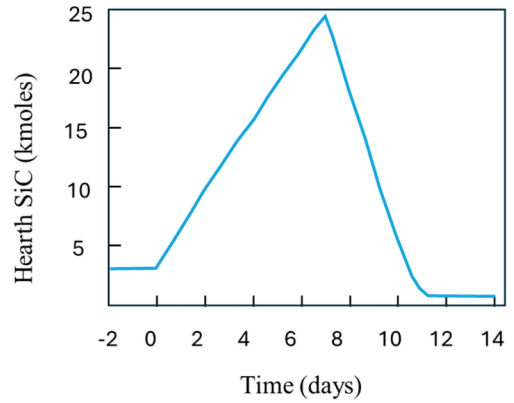
The fitted s values correspond to the SiO pressure between segments Nos. 4 and 5 in the dynamic model. Therefore, the inner zone of the stoichiometric model corresponds to the hearth and some of the lower segments in the dynamic model. The parameter s must be interpreted as the SiO content at the interface between the two zones. It describes the SiO content of the gas that leaves the SiO-producing zone, not the hottest part of the furnace.

Long-term dynamics

The long-term dynamics can be studied using the dynamic model in the continuous feed mode. An example of this application is given in Figure 5.23. The furnace is run close to the optimum carbon content, it is then run one week overcoked and one week undercoked. In practice, the optimum C/SiO₂ ratio will depend on raw material properties, furnace operation, and furnace construction.



a. Calculated results



b. Accumulation of SiC in the hearth

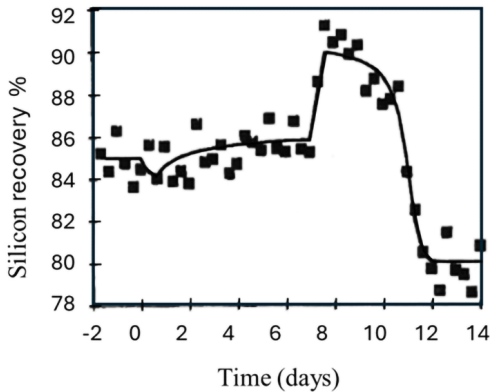
c. Calculated results with $\pm 1.5\%$ random noise added

Figure 5.23 Dynamic behavior according to the dynamic model. A stable period ($C/SiO_2 = 1.85$, close to the optimum C content) is followed by one week with over-coking ($C/SiO_2 = 1.90$) and one week with undercoking ($C/SiO_2 = 1.80$).

In the stable period, the furnace runs at 85 per cent Si recovery. When the C content is increased, the Si recovery drops for some hours. This is because the rate of SiC production increases with increasing C content of the charge, while consumption is proportional to the amount of SiC and therefore does not change initially. As the SiC deposits increase, the rate of SiC consumption and Si production also increases. The Si recovery then approaches asymptotically

a value slightly higher than the stable value before the increase in C content. This increase in silicon recovery means that the assumed optimum value was not correctly determined: the 85 per cent recovery really lies somewhat to the left of the optimum in a graph of the type in Figure 5.17. For a true optimum, an increased C content of the charge would give decreased silicon recovery.

When the C content is decreased after one week, the rate of SiC consumption is high because large SiC deposits are available, while the production of SiC drops. The deposits of SiC will therefore be converted to Si, and the Si recovery increases sharply. However, as the store of SiC is consumed, the rate of Si production decreases and approaches a stationary value corresponding to the new charge composition. The Si recovery therefore has to drop again after some time.

The furnace metallurgist can observe the silicon recovery, but not the accumulation of SiC. In addition, observations from a real furnace contain random noise. The furnace state may therefore easily be misinterpreted if the dynamic behavior is not properly understood. We assume that the metallurgist was uncertain about the carbon content of the charge during stable operation. Therefore, he or she added carbon to the charge at day zero and observed the results. At day 6 there was no clear change in the Si recovery (Figure 5.23c), and he or she decided to lower the C content. Shortly after the change, there was a significant improvement in the silicon recovery, and the operation became fairly stable for about three days. Then the recovery suddenly dropped drastically to a value lower than the value at day zero. The metallurgist might easily think, at this point, that some operational error had occurred.

In the model it is assumed that deposited SiC reacts readily with added SiO_2 . However, experience shows that deposited SiC can be hard to remove, and excess SiO_2 to remove the deposits will often result mainly in increased electrode consumption. This effect is not included in the model.

Short-term dynamics

The stoking mode of the model is most suitable for studying the short-term dynamics. The temperature distribution in a furnace with a stoking cycle of 60 minutes is shown as an example in Figure 5.24. In this case, the height of the shaft is reduced from about 1 metre to 0.5 metre over the cycle period of 1 hour. At stoking, a 25 per cent fraction of the lower shaft materials

is transferred into the hearth zone, and the remaining fraction is pushed down until the interface hearth–shaft reaches the original start position. New charge is then added to the top of the charge to restore the normal shaft height. Immediately after stoking, the lower four segments are hot, while the others are filled with materials at room temperature. SiO_2 reacts with Si in the hearth, and the gas from the reaction passes through the shaft. When the SiO-rich gas meets the cold charge, the condensation Reaction [5.2] releases heat and the temperature rises. Thirty minutes after stoking, segments Nos. 5 and 6 are too hot for condensation, which now runs in segments Nos. 7, 8 and 9. In the hot segments, SiO can be captured in Reaction [6.4] as long as free C is available. Fifty minutes after stoking, the shaft is hot from bottom to top, and condensation runs only in the top segment, where the heat can be given off as radiation to the surroundings.

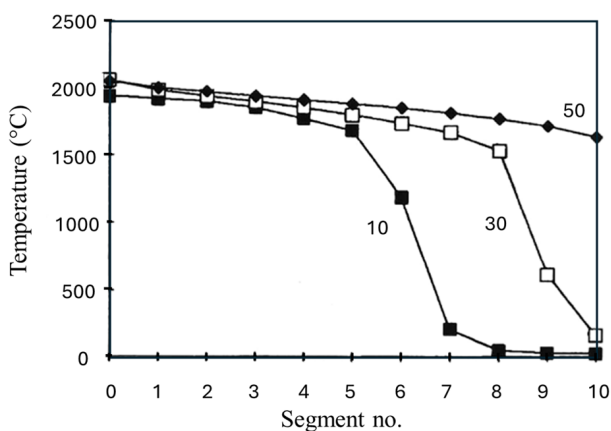


Figure 5.24 The temperature distribution calculated after 10, 30 and 50 minutes in a 60-minute cycle by the dynamic model in the stoking mode.

At the beginning of the cycle, SiO condenses almost completely in the upper layers. However, as the charge heats up to the top, SiO can pass through the charge without condensation and then leave the charge at the top. The amount of SiO lost is shown in Figure 5.25. The furnace blows for about 15 minutes before stoking. This observation indicates that more frequent stokings may reduce silicon loss, conversely, longer stoking periods should increase it. This last idea was tested by calculations. The increased stoking period, however,

changed the overall behavior of the furnace. The temperature of the hearth increased, and the SiO content of the gas became lower. The lowered SiO content more than compensated for the prolonged stoking period.

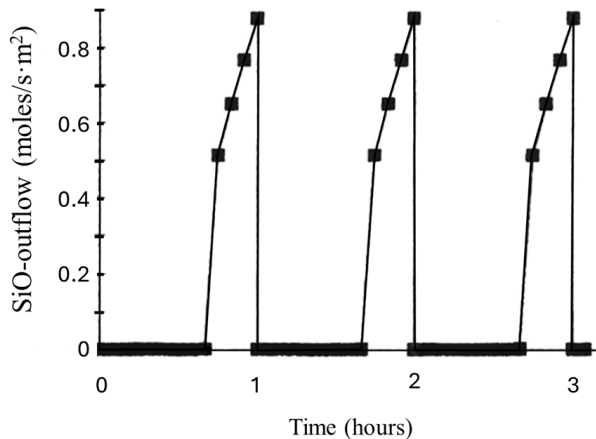


Figure 5.25 The SiO loss from the furnace calculated for the 60 minute cycle by the stoking mode of the dynamic model.

In any study of the stoking process, one must consider how stoking affects the process. The stoking period has to be long enough for the added materials to be completely consumed during the stoking period, otherwise, incompletely reacted raw materials will accumulate in the furnace. Model computations can provide insight that is of great value in such discussions.

Comparison of the modelling concepts

The mathematical models described provide means for different types of simulation. Each approach gives valuable understanding of the process and has applications where it is more suitable than the other models.

The Elkem stoichiometric model is very rapid and simple to use. It has been programmed as a spreadsheet document, and each computation takes only a few seconds. Nevertheless, it can show many of the characteristic properties of the silicon process, and it is suitable for training operators and metallurgists. However, it applies only to steady-state operation and does not show

the approach to steady state. The parameters of the model are lumped, which means that each parameter accounts for several physical effects. Therefore, they are not accessible for independent measurements.

In the Elkem unidimensional model, the shaft parameters have real physical meaning and can, at least in principle, be measured independently. The hearth parameters are lumped, but less so than the parameters of the stoichiometric model. When the model is run in the continuous feed mode, the parameters are averages over the stoking cycle. If corresponding values for the two modes are wanted, the parameters in the continuous feed mode should be adjusted until the two modes predict the same behavior.

The dynamic model is necessary when vertical variations in the shaft, or dynamic variations, are studied. In the continuous feed mode, it records the approach to steady state for a set of parameters. One computation takes several minutes on a powerful personal computer. This mode is suitable for studying the long-term development of the process. If variations within the stoking cycle are important, the model has to be run in the stoking mode. A case with a set of parameters has to be run until a fairly stable stoking cycle is obtained. In principle, the stoking mode can also be used to study the long-term dynamics, but the behavior is more easily seen when the properties are averaged over the stoking cycle.

Several models for various applications have been developed for the silicon process. A universal model will be very complex and most likely never be developed. Useful models require simplification, in which only the properties relevant to the purpose are included as different purposes require different models. Several models of specific zones in the Si-producing furnaces have been developed, such as for tapping, the off-gas system, and the crater and arc.

As a result of developments in computer and sensor technology and AI, more advanced and complex models covering many reaction zones have been possible. These are mainly developed and used by the separate Si and FeSi producers and, in most cases, not published or shared.

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