

## Operational problems

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This chapter gives examples of operational problems where we can gain useful understanding from the inner structure of submerged arc furnaces. The selected examples are:

- Formation of deposits in the furnace
- Tapping

### 8.1 Deposits in the furnace

Formation of deposits is a well-known difficulty in the production of silicon and ferrosilicon. Three main types of deposits have been observed in excavations, as illustrated in Figure 8.1:

- Slag accumulation in the bottom of the furnace as well as on the periphery of the furnace
- $\alpha$ -SiC crusts surrounding the electrodes and as deposits in the lower part of the furnace
- Sintered charge materials in the upper layers of the furnace (also called top-crusts or condensate layer).

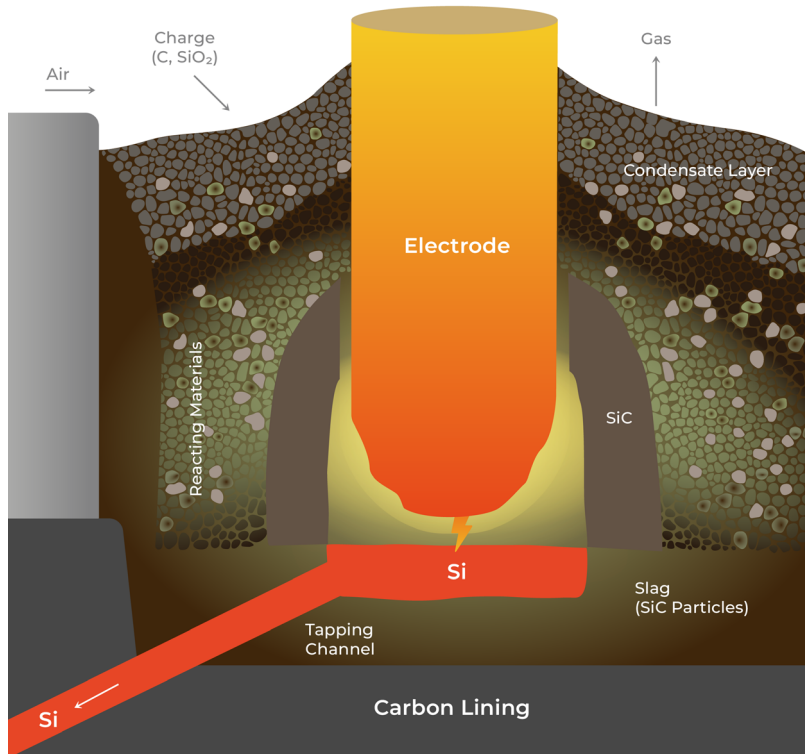


**Figure 8.1** Illustration of deposits in the furnace with 1) a top crust containing condensates gluing the charge, 2) SiC crust around the electrodes and 3) slag deposits in the bottom and on the side periphery of the furnace (Folstad et al., 2020) [With permission from Marit B. Folstad].

The size of the deposits can range from filling large parts of the furnace volume to only small amounts. Deposits leave less room for the production process, hinder material and gas flows, and may affect the electrical current paths. Ideally, the process is run in such a way that deposits are not detrimental to operation. However, if large deposits occur, they must be removed.

## Slag accumulations

The slag constituents in the silicon/ferrosilicon process are mainly SiO<sub>2</sub>, CaO and Al<sub>2</sub>O<sub>3</sub>, as also discussed in Chapter 4. CaO and Al<sub>2</sub>O<sub>3</sub> enter the furnace as impurity elements, and some SiO<sub>2</sub> from the quartz dissolves into the slag

phase. CaO can also be added separately, as e.g. lime, to adjust the properties of the slag. A major part of the added CaO and  $\text{Al}_2\text{O}_3$  will be reduced to Ca and Al and enter the silicon/ferrosilicon. The distribution of Ca and Al between the slag and the silicon can be calculated by the following reactions:



where the underlined elements signify the silicon/ferrosilicon phase and the parentheses denote the compounds in the slag phase. Some slag will thus be tapped together with the silicon/ferrosilicon. Although the amount of slag produced per ton of silicon/ferrosilicon may be low, slag may accumulate in the furnace and hence take up a large volume. The slag accumulated in the furnace is thus a  $\text{SiO}_2$ , CaO,  $\text{Al}_2\text{O}_3$  slag. Its  $\text{CaO}/\text{Al}_2\text{O}_3$  ratio is determined by the raw material composition, but the  $\text{SiO}_2$  content will vary from 30wt% and up, as shown in Figure 8.2.

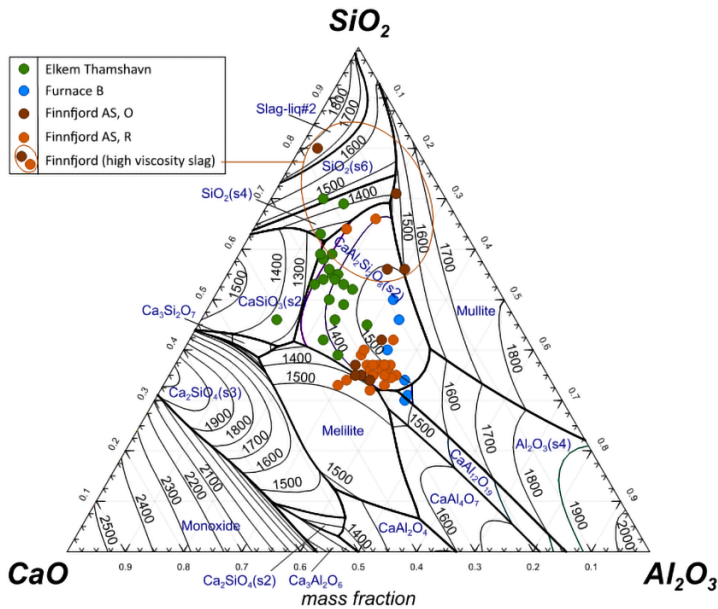


**Figure 8.2** Tap slag from industrial silicon and ferrosilicon furnaces. The same figure is shown in Chapter 4 as Figure 4.3 (Folstad, 2023). [With permission Marit B. Folstad].

The viscosity of the slag is higher than the viscosity of silicon/ferrosilicon. Hence, slag flow out of the furnace is much more sensitive to temperature and composition variations than silicon/ferrosilicon flow. The viscosity is also affected by SiC particles in the slag. Slag wets SiC particles, so SiC particles will readily enter the slag phase from the silicon/ferrosilicon phase. The size and amount of SiC particles in the tapped slag will be lower than in the accumulated slag, as illustrated in Figure 8.3. As a result, slag flow will be slower than silicon/ferrosilicon flow in the furnace and will therefore accumulate in the lower part of the furnace. This will happen especially if the temperature in the lower part of the furnace is low, due to high electrical current paths in the furnace. A lower temperature affects the following three issues:

- As the slag viscosity is very temperature dependent, a low temperature will increase the viscosity of the slag phase.
- When the slag is heated to a high enough temperature, it will interact with the SiC and the  $\text{SiO}_2$  will be reduced to elemental silicon. If the temperature in the high-temperature zone is too low, the  $\text{SiO}_2$  will not be reduced and the slag will have a high  $\text{SiO}_2$  content. The viscosity increases with increasing  $\text{SiO}_2$  content in the slag (as discussed in Chapter 4), and hence the viscosity of the slag will be high.
- With the same argument as in the previous point, if the temperature in the high-temperature zone is low, the SiC particles in the slag will not react with the  $\text{SiO}_2$ , and hence there will be more SiC particles in the slag.

During excavations, slag has been found all the way at the top of the charge, at the periphery of the furnace. How the slag has formed or arrived in the upper part of the furnace is not known. There is not enough  $\text{CaO}$  and  $\text{Al}_2\text{O}_3$  content in the raw materials to represent the slag composition, and hence it is believed to be coming from the bottom slag layer. There is overpressure in the high temperature zone of the furnace due to the high gas formation rate, and it has been calculated that this may press the silicon, and thus maybe also the slag, towards the furnace periphery (Kadkhodabeigi, 2011). If the pressure is high enough, slag may also be pressed upwards. The slag will freeze as it moves towards areas of lower temperatures, and the state of the slag is illustrated in Figure 8.4. At high temperatures, the slag will be liquid, and it will start to solidify at lower temperatures. In this figure, the slag composition is taken from excavations and the temperature is calculated (Folstad, 2023; Myrhaug, 2020).

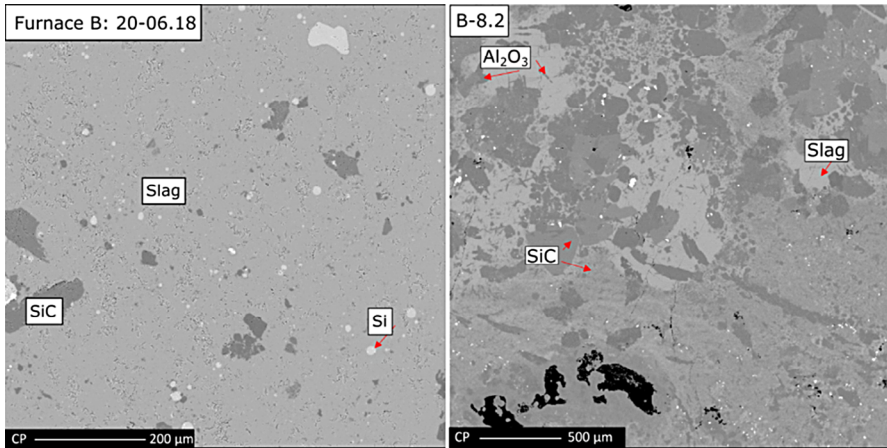


**Figure 8.3** EPMA image of a tapped slag sample to the left and an accumulated slag sample to the right collected during excavation. Both samples are from the same furnace (Folstad, 2023). [With permission Marit B. Folstad].

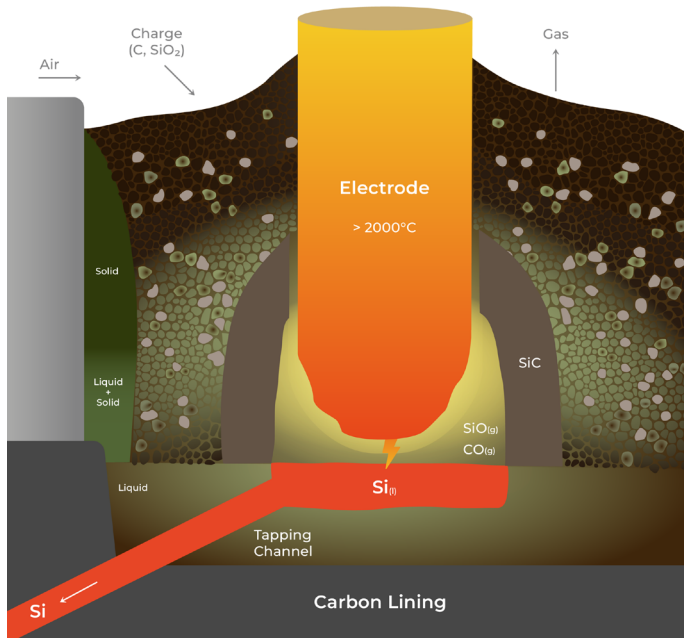


**Figure 8.4** Estimation on how the slag composition will be in the furnace; liquid, liquid + solid, or solid, based on calculated temperatures. (Folstad, 2020). [Used with permission from M.B. Folstad].

Slag is also important for other silicon-containing production processes, such as silico-manganese, silico-aluminium and silico-calcium. In carbothermic production of silico-aluminium, the charge components react and give a mixture of aluminium oxide and aluminium oxy-carbides (Motzfeldt *et al.*, 1989). This mixture has some fluidity and sinks into a layer at the bottom of the furnace, but it is not fluid enough for tapping. The electrical conductivity is so high that resistance heating is impossible, so it must be heated by an electric arc above the melt. At the same time, this arc heats the charge higher up in the furnace, and a large fraction of the energy is used to melt new materials. As a result, the furnace is filled with incompletely converted raw materials unless it is possible to control the flow of materials into the inner zone. An illustrative example is a series of tests (unpublished Elkem work) to produce an alloy 60% Si and 40% Al from compound pellets [ $\text{Al}_2\text{O}_3 + 3 \text{SiO}_2 + 9 \text{C}$  (petroleum coke)]. The first tests were run in a 50 kW furnace with split furnace body. The resistance became very stable, and the charge sank down evenly without any stoking. The energy consumption in the very small furnace was 14 MWh/ton, which corresponds to an Al and Si recovery well above 90 per cent. When the process was transferred to a 500 kW furnace, the charge sank too rapidly and formed a highly conducting oxide melt. The furnace controller raised the electrode to a high position, and the heat produced more slag instead of completing the reaction.

## Deposits of SiC

If more carbon is added in the raw materials than is consumed through the silicon- and SiO- formation, the carbon surplus will be transformed to SiC and accumulated in the furnace. The stoichiometric model (Figure 3.12 and Figure 9.6) demonstrates that an optimum C content gives a maximum silicon recovery at given operational conditions. If the C content is lower than the optimum, all the intermediate SiC is consumed, but the loss as SiO is higher than at the optimum. Some SiO is lost even at the optimum C content. If the metallurgist tries to increase the silicon recovery by increasing the content of C above the optimum, the loss as SiO will decrease as expected, but the silicon loss as accumulated SiC more than balances the gain. This SiC is deposited

in the lower part of the furnace, in the high temperature area, and when the deposit becomes large, it will obstruct operation severely. The optimum C content depends on the state of the furnace, and it is therefore not a fixed quantity that can be used permanently. The furnace metallurgist must observe the operation continuously and determine whether the C content is close to the optimum. Most plants today have models to calculate the carbon balance daily, i.e., the deviation between the carbon added and the carbon consumed. However, as no measurement is 100% correct (e.g. the analysed Fix C content in the raw materials and the raw materials weights at the plant, to mention a couple), one can never find the true optimal carbon content. By definition, one will always add more than is consumed, or less than is consumed, though the difference may be small in a well-operated plant.

One strategy is to run with a C content so low that there is always a safe C deficit relative to the optimum. A small excess silicon loss as  $\text{SiO}$  is acceptable during successful operation, but because the correct C content is not constant, it is easy to operate with too low an addition. Today, silicon recovery of 80–95 per cent is typical. Safe operation is complicated by effects omitted from the simple stoichiometric model, which assumes that excess  $\text{SiO}_2$  always reacts with  $\text{SiC}$  in the inner zone. In real operation, however, the  $\text{SiO}_2$  will also react with the electrode. As a result, safe operation can lead to unnecessarily high electrode consumption, which adds strongly to the cost of silicon.

The accumulated  $\text{SiC}$  may appear in at least three different states:

- Carbon particles (charcoal, coal, char, coke...) that have been transformed to  $\text{SiC}$ . This has not been seen during excavations, however, one would not be able to separate  $\text{SiC}$  particles that are in surplus from those that take part in the production process. A surplus of transformed carbon particles has, however, not been seen in the lower part of the furnace. It can also be mentioned that  $\text{SiC}$  particles have very low strength and may crumble over time or be transformed to other states (Hoover, 2023). The transformed carbon materials are  $\beta$ - $\text{SiC}$  at temperatures below  $2000^\circ\text{C}$ . This will not be further discussed in this chapter, as the formation is already covered previously in this book, e.g. in Chapter 2.

- Small SiC particles that are mixed with the silicon and the slag. If the amount of this SiC is too high, it will, as described above, hinder silicon and slag flow and, in the end, lead to a crust-like material in the bottom of the furnace. This is due to the slag (as described above), the SiC particles, or a combination of these two factors. This SiC is found to be  $\beta$ -SiC, however, it has a much denser structure than the transformed raw materials and is believed to come either from precipitated SiC when the silicon experiences temperature changes, or from the reaction between Si and CO gas,  $2\text{Si} + \text{CO} = \text{SiO} + \text{SiC}$ , which is the reversed silicon producing reaction.
- $\alpha$ -SiC crust surrounding the electrodes. This crust has been non-existent in some excavations, but in others it has been seen in large volumes (Ksiazek *et al.*, 2016; Tangstad *et al.*, 2014).

### ***Formation of SiC in liquid silicon***

When we add energy to a deposit of Si-containing SiC, the temperature rises. The phase diagram in Figure 8.5 and Figure 8.6 gives an indication of the behavior. As the temperature increases, the solubility of carbon in silicon becomes higher. Very close to the arc, where the temperature may be several thousand degrees, the carbon solubility may be at a percentage level, however, below 2000°C the solubility is at ppm level. When the silicon experiences temperature differences, it will dissolve SiC as the temperature increases and then precipitate SiC when it cools down again. If this was a closed system, the amount of SiC particles would be constant at a given temperature. However, it is seen in other systems, such as silicomanganese, that the metal dissolves other carbon materials available faster than the precipitated SiC, and in that case, the amount of precipitated SiC will increase over time (Davidsen, 2011). This may also happen in the silicon/ferrosilicon system.

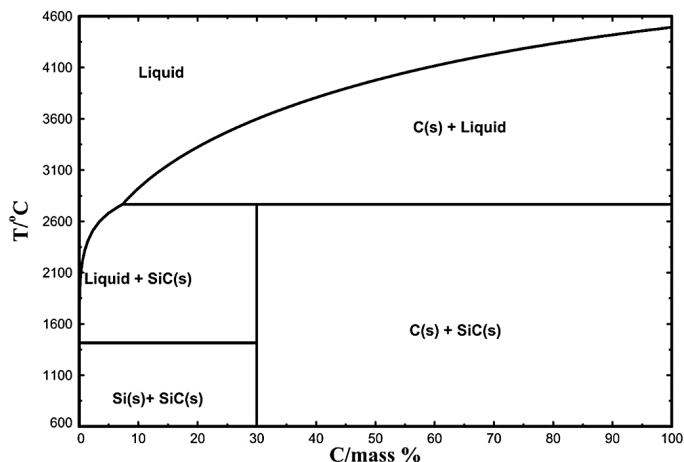


**Figure 8.5** (Figure 2.2 in Chapter 2) The Si–C binary phase diagram calculated by the use of FactSage using the FTLite database.

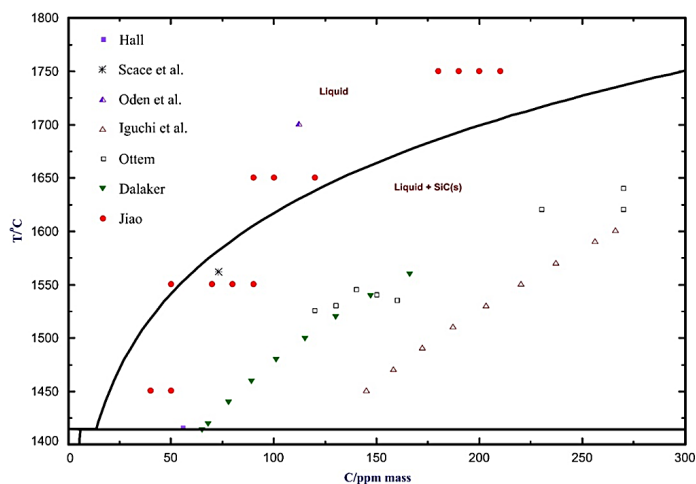


**Figure 8.6** (Figure 2.3 in Chapter 2) The content of C in silicon in equilibrium with SiC summarized by (Jiao, 2020) (Hall, 1958; Scace, 1959; Oden, 1987; Ottem, 1993; Iguchi, 1993; Dalaker, 2009). [With permission from J.M. Jiao].

### ***The formation of $\alpha$ -SiC crusts***

Varying amounts of SiC crusts have been found in industrial furnaces during excavation. When there is a large amount of SiC crust, it may look as shown in Figure 8.7. Figure 8.8 shows that the crust is a dense material with gas channels, as also shown in Figure 8.9. Crystal formation can also be seen on the surface of the crust (Ksiazek *et al.*, 2016; Tangstad *et al.*, 2014; Tranell *et al.*, 2010).

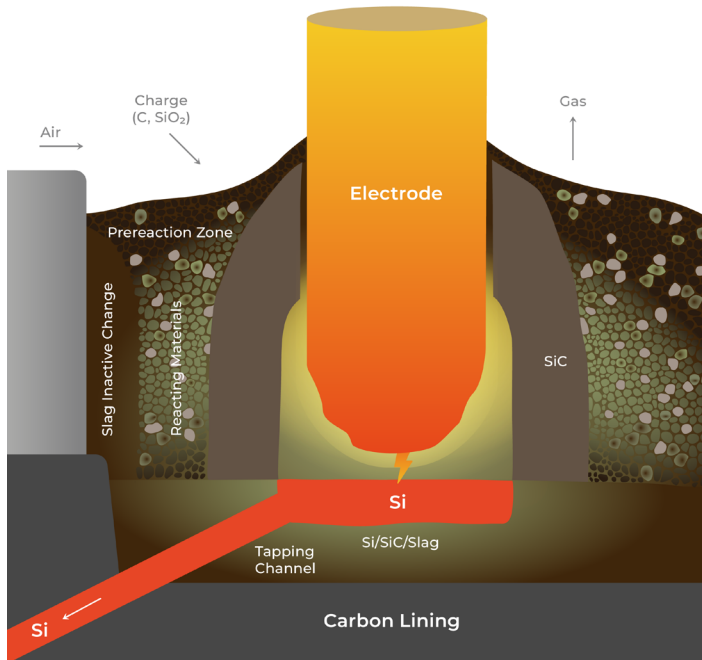


**Figure 8.7** a) General illustration of SiC crust and b) Schematic view of SiC crusts found during an industrial excavation (Folstad *et al.*, 2020; Tangstad *et al.*, 2014). [Used with permission from M. Folstad].

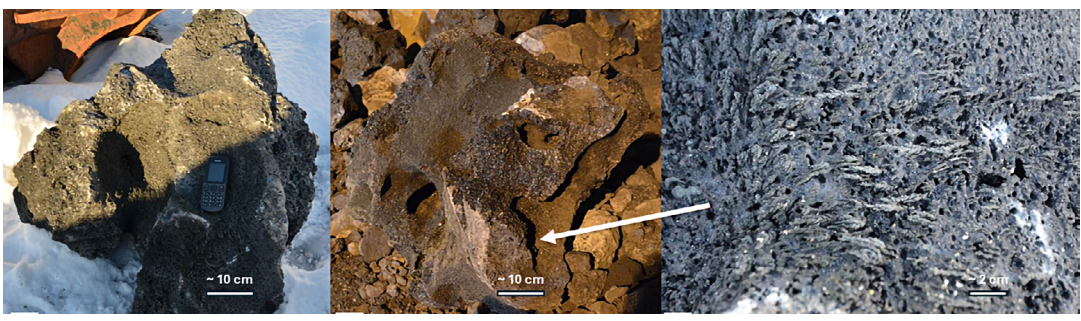


**Figure 8.8** Pictures of SiC crust excavated from an industrial furnace (Tangstad et al., 2014).

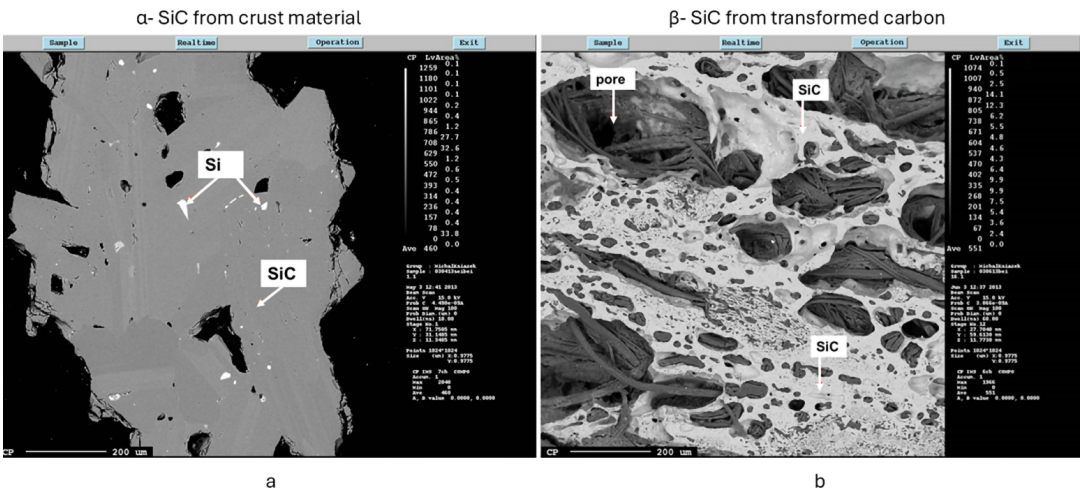
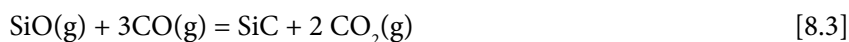


**Figure 8.9** Comparison of  $\alpha$ -SiC structure (a) to  $\beta$ -SiC transformed charcoal (b) (Jayakumari, 2020) [Used with permission from S. Jayakumari].

$\alpha$ -SiC is stable at high temperatures. Transformed charcoal, coal and petcoke have been observed to start transforming around 2100°C as shown in Figure 8.10. The transformation rate is also dependent on the original carbon material, as well as the amount of Si present. SiC from charcoal is seen to transform faster than SiC from coal and petcoke, and a higher amount of silicon in the structure will also increase the rate, as seen in the figure. In both laboratory samples (Jayakumari and Tangstad, 2020) and industrial samples (Figure 8.8 (Ksiazek *et al.*, 2016; Tangstad *et al.*, 2014)), crystals can be seen growing on the surface of the carbon particle. It has been proposed (Jayakumari and Tangstad, 2020) that the reaction proceeds via a gas reaction with activated atoms on the SiC surface and in the pores:



Because the surface and pores serve as nucleation sites, highly porous material, like charcoal, will react faster. The  $\text{CO}_2$  formed will instantly react with SiC to produce SiO and CO gas, hence, the overall  $\text{CO}_2$  pressure is very low at these temperatures.

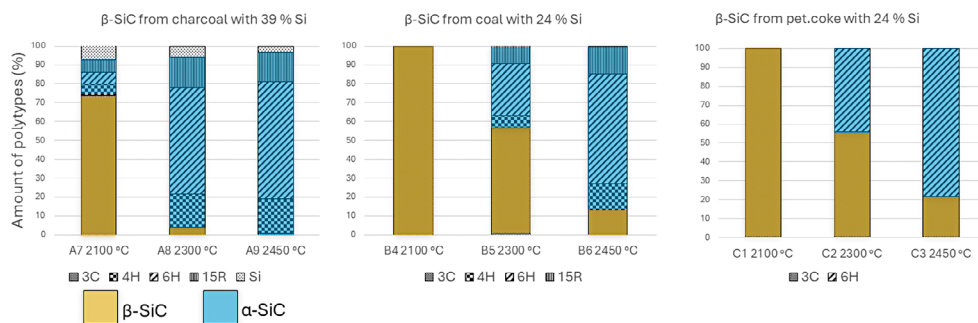


**Figure 8.10** Extent of transformation from  $\beta$ -SiC to  $\alpha$ -SiC for charcoal, coal and petcoke at increasing temperatures (Jayakumari, 2020; Jayakumari and Tangstad, 2020) [Used with permission from S. Jayakumari].

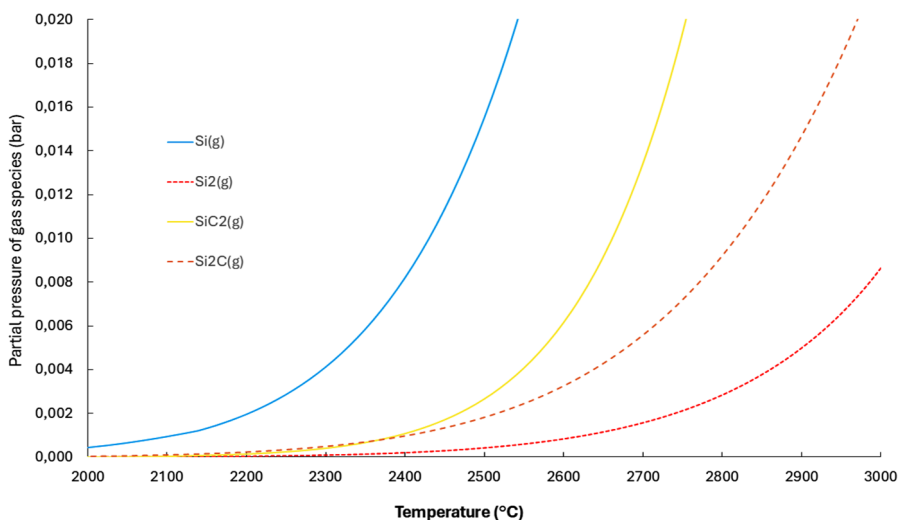


**Figure 8.11** Gas pressures of Si and SiC<sub>x</sub> species from 2000–3000°C calculated at HSC Chemistry.

It has also been discussed if the  $\alpha$ -SiC is formed from gas species formed around the arc. Close to the arc, the temperature may be several thousand degrees, and if no oxygen is present in this area, there may be a high amount of gaseous Si and SiC<sub>x</sub> species, as seen in Figure 8.11. As the gas species flows away from the arc, the temperature in the gas will drastically decrease down to around 2000°C, and the gas species will condense or react to form Si and SiC and an  $\alpha$ -SiC crust.

Whether it is the temperature alone that transforms  $\beta$ -SiC to  $\alpha$ -SiC, or whether it goes through the SiC<sub>x</sub> gas species, is to date not known. However, both mechanisms require high temperatures and can thus only occur close to the electrodes. As the  $\alpha$ -SiC crust has higher electrical conductivity than a bed of charge/bed of SiC particles, it is believed that much of the electrical energy is being produced in the SiC crust in addition to the arcs (Hoover, 2023). This means that when the charge meets the high-temperature SiC crust, the metal production may mainly form on the crust and not in the bottom of the furnace as previously described.

### ***The removal of deposits***

In principle, the Si–SiC deposits can be removed with excess SiO<sub>2</sub> in the charge. The Si loss will increase, since the charge now has a lower content of C than normal to react with SiO, but much of the energy and silicon in the deposit will still be recovered. However, SiO<sub>2</sub> tends to attack the electrode instead of the bottom deposit, and the electrode consumption increases strongly.

The concentrated heat of the arc can vaporize the SiC-Si deposit material that comes close to the arc. In a stationary furnace, the electrode tip can go close to the bottom by arcing, but it will dig a rather narrow hole. In a rotating furnace, it can dig a circular trench, but it cannot widen the trench to the sides. Perhaps the best removal of bottom deposit would be obtained if the electrode had a slow circular movement relative to the pot. The diameter of the circle could be perhaps some 20 centimetres.

### **Formation of crusts in the upper parts of the charge**

Normally, the charge can be broken down around the electrode during the stoking operation, and a ring-shaped opening is formed around the electrode. When the furnace is open 30–40 cm from the electrode, stoking and charging is easy, and the gas distribution becomes uniform. The charge particles outside this opening are sintered together by silica and condensate, as discussed also in Chapter 2. Occasionally, the opening becomes very narrow. Then stoking becomes difficult, and the new charge does not give a layer that distributes the gas uniformly. The gas from the inner zone breaks out where the charge layer is thinnest. The result is a poor counter-current process, resulting in blowing and low silicon recovery.

The crust formation relates to the following condensation reactions, also described in Chapter 2:



When the operation starts from an empty furnace, the new charge is loose. In the high temperature part, around the electrode tips, SiO and CO gas is formed and flows into the colder part of the furnace, both the passive and

active part of the furnace. SiO and CO gas will diffuse into the colder materials and gradually fill the voids with  $\text{SiC} + \text{SiO}_2$  and  $\text{SiO}_2 + \text{Si}$ , also called condensates. The term ‘condensates’ is not, strictly speaking, correct for these materials, however, due to the long industrial tradition of using it, it will also be used here. The mass in the condensation layer will be partly molten  $\text{SiO}_2$ , condensate and C materials partly converted to SiC. The condensation reactions are exothermic, and hence an increased amount of condensation will heat the top part of the charge. The condensates and the raw material mix forms a sintered mass that is difficult to break. When the active mass around the electrodes is stoked down, new, cold material will enter. This sequence is repeated in every stoking cycle. The high content of condensate and viscous silica makes the mass difficult to break.

The crusts may sometimes be weakened by heat from the electrode if the electrode is run in a high position, and then it may be possible to stoke them down. For very strong crusts, even blasting with explosives has been tried. When the remains of the crusts are brought down into the crater and heated, they react readily.

## 8.2 Tapping

The tapping efficiency is determined by the structure of the zones and the distribution of materials inside the furnace. The inner structure of the furnace is described in Chapter 3. The product is tapped from the furnace through a tubular hole that reaches into the zone where the silicon is molten at the bottom of the furnace. The tapping of the furnaces, that is, the drainage of the liquid silicon and some minor slag amounts, is an important sub-process, both economically and from an HES point of view. If the furnace is not drained properly, it will affect the Si-yield, as more SiO gas is produced and lost. The extent of drainage will also affect the electrode tip position and hence the electrical current paths. If the drainage has been too low for some time, liquid silicon will accumulate in the furnace. When the liquid metal is finally drained, the high amount of metal draining at high speed may cause both material and human damage. The discussion on the correlation between the furnace zones and the tapping is based on the paper describing the conceptual tapping of a silicon/ferrosilicon furnace (Tangstad *et al.*, 2021).

## Conceptual tapping model

Tapping can be continuous or discontinuous. Ideally, the furnace is emptied rapidly when the tapping is discontinuous, but often the flow of alloy is rather slow, and the taphole is open most of the time. Then the real difference between continuous and discontinuous tapping is moderate.

Typically, one taphole is used at a time in the tapping of a silicon furnace. This means that the liquid silicon must flow through three different areas, as illustrated in Figure 8.12:

- Step 1: The liquid silicon must flow from the back electrodes to the tap-electrode area.
- Step 2: The liquid silicon must flow to the taphole, that is, through the material between the high temperature area, close to the tap electrode, and the taphole.
- Step 3: Through the taphole.

The tap rate can be determined by the sum of the resistance in these three steps. The tap-electrode is here defined as the electrode closest to the taphole. As the furnace pot is rotating, there will be two electrodes that have the same distance to the taphole at a fixed time. This is, however, only happening over a small time period.

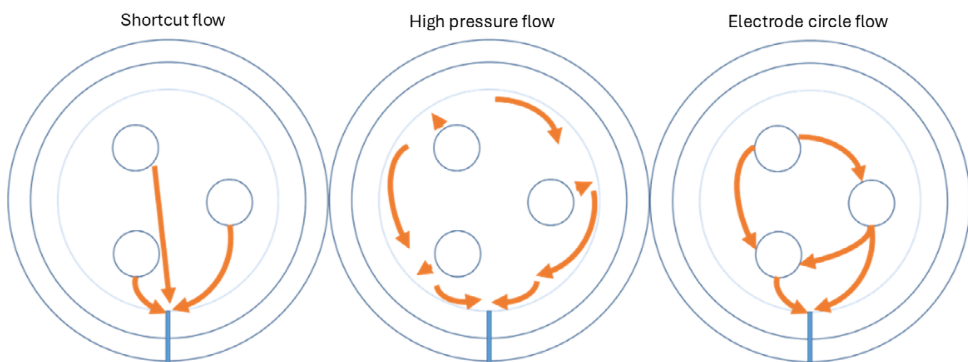


**Figure 8.12** Possible flow patterns from back electrodes to taphole area.

In principle, one can visualize Step 1 in three conceptually different flow patterns, as illustrated in Figure 8.12. The simplest flow model for metal flow from the back-electrodes to the tapping hole is to visualize the furnace as a simple container holding a liquid, as also illustrated in Figure 8.13. The metal will then flow according to the shortcut flow model shown in Figure 8.12. This model assumes that the flow resistance and gas pressure are the same throughout the furnace, and the liquid will therefore take the shortest path from the electrode area, where it is produced, to the taphole. However, this is rarely the case in industrial furnaces, owing to pressure gradients and to materials that hinder flow.

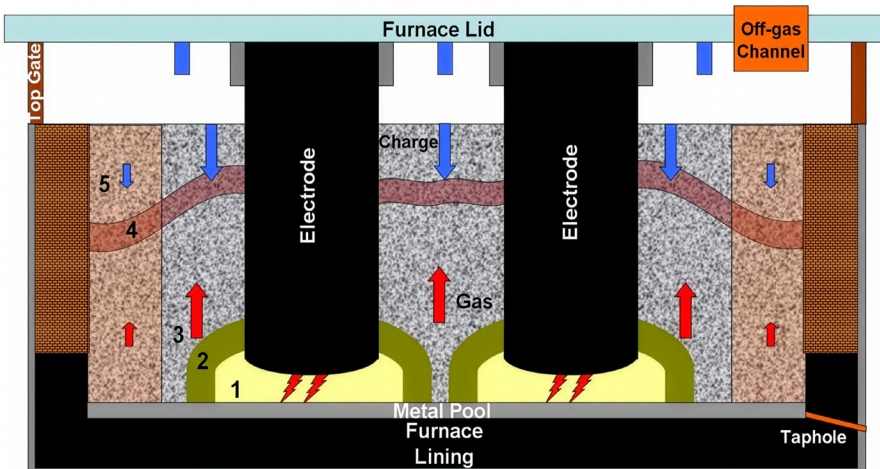


**Figure 8.13** A cut-through, graphical depiction of the submerged arc furnace used in high-silicon alloy production. Different zones have been formed in the charge, such as the crater zone (1), crater wall (2), softening and melting zone (3), crust formation zone (4), and stagnant charge zone (5) (Kadkhodabeigi, 2011). [Used with permission from M. Kadkhodabeigi].

Kadkhodabeigi (2011) modelled the tapping flow from a Si and FeSi furnace based on the zones illustrated in Figure 8.13. In this model, Step 1 and Step 2 cannot be separated because there is a continuous metal bath in the lower part of the furnace. As seen in Figure 8.14, an overpressure of 3–4 kPa (30–40 mbar) has been measured in industrial furnaces due to gas production, and the pressure will therefore vary with the load, as seen in the figures. For a furnace with a horizontal, continuous metal pool, Kadkhodabeigi calculated that the metal would be pushed towards the side lining, as seen in Figure 8.15, using overpressures from 30–200 mbar in the calculation. This effect is also illustrated in the high-pressure flow model in Figure 8.12. The metal will therefore run along the lining wall to the taphole position. When the metal in front of the taphole no longer fills the taphole, the tapping rate will decrease, as illustrated after 350 seconds in Figure 8.15.

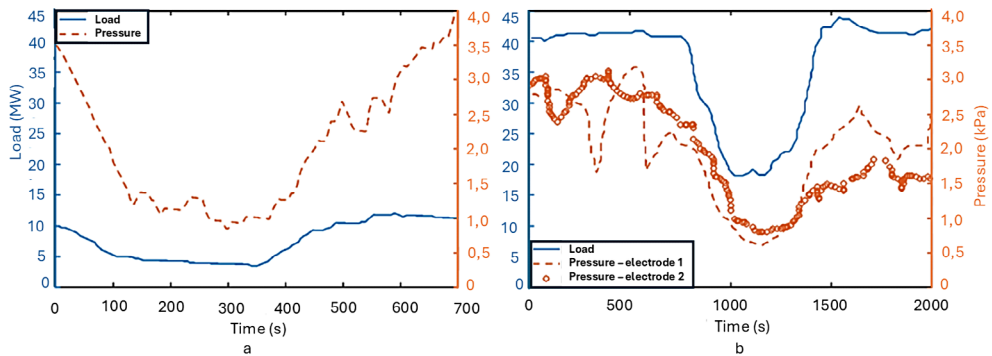


**Figure 8.14** Direct relation between crater pressure and furnace electric load, based on industrial measurements from different submerged arc furnaces used in silicon production (after Grådahl and Johansen, 1998; Tveit et al., 2002).

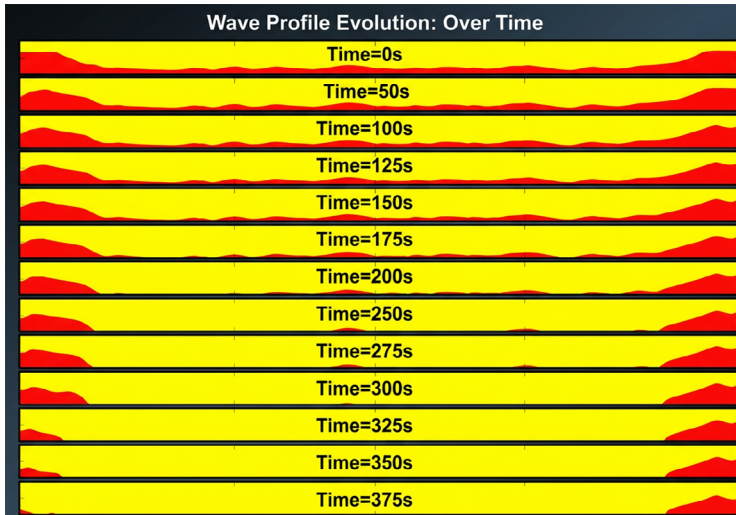


**Figure 8.15** Evolution of the metal pattern in the lower part of the central plane of the ferrosilicon furnace. This explains the reason for the sudden flow rate drop during furnace tapping when the metal level in front of the taphole decreases (Kadkhodabeigi, 2011). [Used with permission from M. Kadkhodabeigi].

Though the higher pressure around the electrode tips is an important input to a model, other effects should also be included. First, as the metal is pressed into the cold, stagnant charge zone (also called the inactive zone), it will cool and may not have a warm, open space to flow into. Second, excavations have seldom shown an open metal pool in the bottom of industrial furnaces (Folstad and Tangstad, 2021; Folstad *et al.*, 2020; Ksiazek *et al.*, 2016; Tangstad *et al.*, 2014). (It must, however, be noted that when an excavation gets close to the furnace bottom lining, debris and materials from the rest of the furnace fall in, and the picture may not be so clear.) Figure 8.16 shows schematic pictures of various zones that have been found during excavation of industrial furnaces. It can also be noted here that the metal must be drained through a zone of slag with SiC particles, called the tapping channel, before it enters the taphole. The taphole is defined here as the channel through the hardware of the furnace, that is, the channel through the lining and the steel shell.

One pattern found under the electrode is a metal pool surrounded by a slag layer (Tangstad *et al.*, 2014), as illustrated in Figure 8.16 and Figure 8.17. The slag found in the lower part of the SiC furnaces is believed to be liquid, as the liquidus temperature is around 1500°C (Folstad and Tangstad, 2021),

and the metal is tapped at 1800–1900°C (Ksiazek *et al.*, 2018; Werner, 2019). The temperature in the slag layer is, however, very dependent on the electrical current paths and the heat transfer in the furnace. Even though the slag is liquid, it is probably quite viscous, especially because it contains SiC particles. This also explains the accumulation of slag over time, as it is not being drained from the furnace. The metal pools below the electrodes may, however, form a ring of metal in the electrode motion path, as the furnace is rotating. This means that the metal will follow the electrode path during tapping, as shown in the electrode circle flow in Figure 8.12.

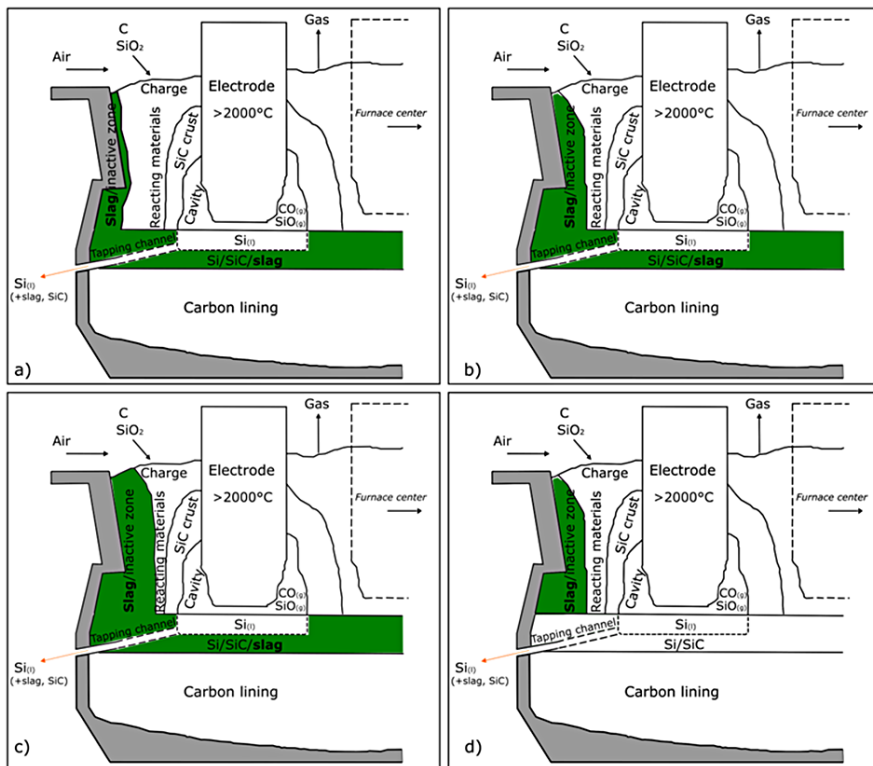


**Figure 8.16** Schematic figures illustrating the various zones in a Si furnace. The first case, a), shows an ideal situation with almost no slag along the furnace walls. The second case, b), shows an average situation, with a layer of slag/inactive zone that affects furnace operation. Case c) shows an accumulated furnace. The last case, d), shows the situation with no slag and SiC in the furnace bottom (Folstad and Tangstad, 2021). [Used with permission from Marit B. Folstad].

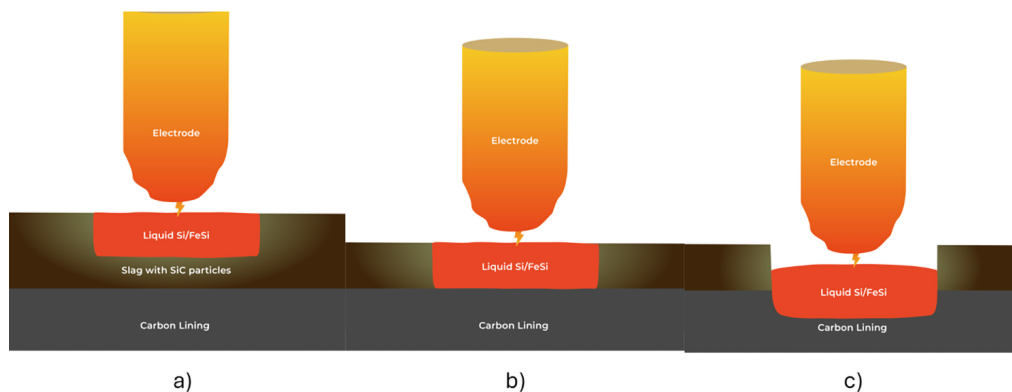


**Figure 8.17** Possible configurations of the metal pool under the electrode tip, surrounded by slag with SiC particles: a) high electrode positions due to a high amount of accumulated slag (Ksiazek et al., 2016) (Wacker 1); b) optimal electrode position; c) low electrode position due to lining wear (Tangstad et al., 2014).

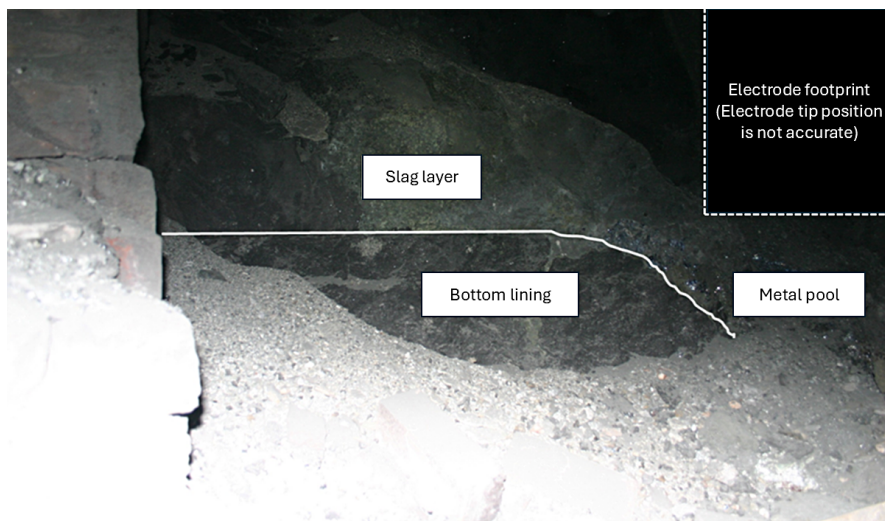


**Figure 8.18** Picture from excavation of Si furnace (Tangstad et al., 2021).

So far, mainly Step 1 has been discussed, that is, the drainage from the back-electrodes to the tap-electrode. If this is modelled, by e.g. Computational Fluid Dynamics, any obstacles in the furnace will lower the tapping rate for some time, until the tapping rate again reaches the production rate. Obstacles include solidification of metal in cold areas, but in the models the effect on electrodes and furnace operation is typically not included. This may, of course, also reveal that the main problem is not Step 1, drainage from the back electrode to the taphole electrode, but actually Step 2: drainage from the tap-electrode, that is the hot area of the furnace, to the taphole, which is in the colder region (Folstad *et al.*, 2020).

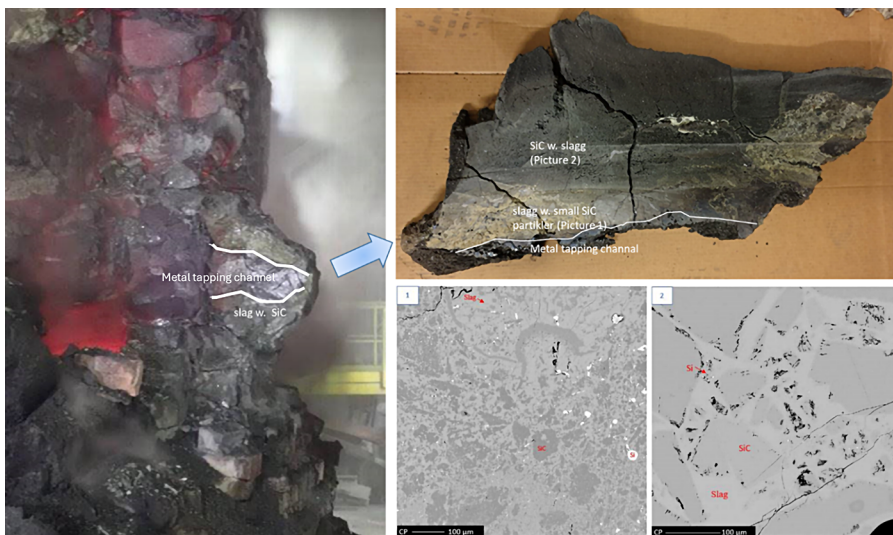


**Figure 8.19** Tapping channel from industrial excavation (Folstad *et al.*, 2020). The left picture shows the tapping channel, the top-right picture shows the top of the same tapping channel, and the pictures below show the SiC particles in the slag matrix from two different areas (Folstad and Tangstad, 2021). [Used with permission from Marit B. Folstad].



**Figure 8.20** *Tapping channel from taphole through a slag layer (Tangstad et al., 2021).*

In a couple of industrial excavations, shown in Figure 8.18 to 8.20, where the excavation of the tapping area has been more focused, it is seen how the metal must flow through a more than 1 m thick slag zone before entering the taphole. The colour of the slag is often determined by the amount and size of SiC particles, as the darker area has more and larger SiC particles. It is therefore believed that the type and amount of slag in the proximity of the taphole will be important for the total drainage of the furnace (Folstad *et al.*, 2020).

Both large amounts of  $\alpha$ -SiC crusts and smaller amounts have been observed in silicon furnaces. Though not verified, it seems that the SiC crusts are not present all the way down to the metal pools, hence, their influence on tapping is still an open question. It is, however, believed that the SiC crusts will distribute the electrical current paths a bit wider around the electrodes, and thus actually heat the area close to the electrode. This may affect the flow properties of both slag and metal.

Step 3, flow through the taphole, is dependent on the dimensions and maintenance of the taphole. There is not much information on this specifically for the silicon process, but more general information can be found in the extensive review by Nelson and Hundermark (2016).

High viscosity slag, that is, slag with a high  $\text{SiO}_2$  content, low temperature, and SiC particles, can all lead to clogging of the taphole or tapping channel (Folstad, 2023). This is also discussed in Chapter 4. This slag will form balls or tubes as it exits the furnace. Partly transformed raw materials, like partly molten quartz or SiC particles, may also be tapped together with the silicon and slag. This is not seen during excavations in the high temperature area, and one may speculate whether materials from the inactive zones may come through uncontrolled tapping channels through the lining. Several methods are available to remove the obstacles, such as penetrating with powerful mechanical equipment, burning with a graphite electrode, or blowing with oxygen.

## Gassing through the taphole

During normal tapping, silicon evaporates from the molten silicon and some smoke emerges. Occasionally, however, an intense, several metre long jet of burning gas emanates from the taphole. The taphole is said to be gassing or blowing. The gassing may disappear after a few hours, but sometimes it will go on for more than a week. If the gassing taphole is plugged and a new hole is opened, it will often start gassing shortly after. This observation indicates that the gassing often has a cause within the furnace and not in the outer part of the taphole. The gassing often starts without any warning. The production rate seems to be normal, but it drops significantly when the furnace gasses. Sometimes it has been observed that a lot of slag is tapped just before the gassing begins. Taphole blowing is a serious challenge in the (ferro)silicon process, as it means lower production, unpleasant working conditions in the tapping area, and generally smoke pollution of the internal environment of the plant.

To avoid taphole gassing, it is important to know the reason for it. General understanding of gas flow tells us that gassing through the taphole requires some overpressure in the inner zone of the furnace and an open channel from the overpressure through the taphole. Since the inner zone of an operating furnace produces gas, there will always be an overpressure that is large enough to push the gas out through the outer zone, as seen in Figure 8.14. Measurements of the crater pressure in production furnaces show that the overpressure varies strongly, but it is seldom larger than 0.1 bar (Grådahl *et al.*, 1997; Ingason, 1994; Johansen *et al.*, 1998; Tveit *et al.*, 2002). There is

a strong high-frequency variation, but generally the pressure is largest just after charging, and smallest when the furnace is ready for stoking. According to our comprehension of the inner structure of the furnace, the cavity is surrounded by a SiC wall. This SiC wall has, however, gas channels and will not be gas tight. The bottom consists of Si or slag containing SiC crystals. From calculations, it is seen that if the taphole is covered by slag or silicon, the gas will be forced from the crater through the charge (Kadkhodabeigi, 2011). If, on the other hand, the metal or slag is not covering the taphole, and additionally the charge has a low permeability due to too much condensate in the upper zone, the gas will exit the furnace through the taphole.

The metallurgist can, in principle, reduce the overpressure by establishing a porous outer zone with a low pressure drop. However, there will always be some overpressure in the furnace, and the main approach to the gassing problem must be to avoid leakage in the bottom gas sealing. Such leakages can be caused by damage to the taphole or a too-steep taphole that leads into the cavity or into cracks in the deposit. Often, however, it seems that the cause is inside the taphole. In that case, the gassing is often related to low electrodes. When the furnace is run with a long-term carbon deficit, the Si–SiC layer at the bottom will be consumed gradually, and the electrode will go deep and make the bottom very hot. The Si–SiC layer becomes thin, while slag and silicon become fluid and flow out with the tapping. Some solid slag and alloy close to the wall will melt, and gas passages through the crater wall may form. The result is that the gas-tight SiC–C layer at the bottom will leak. To stop the gassing, the metallurgist can use corrections that raise the electrodes. Practical means are higher voltage or increased carbon content of the charge. The low electrode position is an obvious suspect when the taphole gasses, since we can easily imagine the mechanism.

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