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Pilot-Scale Silicon Production Using SiC as Reduction Material – Opportunities and Operational Challenges

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Abstract – Elkem is developing a two-stage silicon production process in which silicon carbide (SiC) is first produced in a dedicated reactor and subsequently used as a reducing agent in a second reactor. This approach can reduce direct emissions of dilute CO_2, enable utilisation of a concentrated CO stream, and lower energy consumption and costs. As part of this development, a pilot-scale submerged-arc furnace has been designed and constructed at Elkem's R&D facilities in Kristiansand to demonstrate silicon production with high SiC fractions in the reduction material. To date, five pilot campaigns have been conducted with progressively increasing SiC fractions, ranging from a reference case without SiC to approximately 60 percentage points SiC in the carbon coverage. The main objective of these campaigns has been to establish operating strategies for subsequent demonstration campaigns. Material balance analyses show that silicon can be produced with a high fraction of SiC. The best campaign achieved a silicon yield of 92% based on tapped metal and 88% based on filter dust, with a specific energy consumption of 11.8 MWh per tonne Si. A solid basis has been established for the planning of forthcoming demonstration campaigns.

1. INTRODUCTION

Industrial production of silicon has, in principle, remained largely unchanged for more than 100 years. Carbon-based reduction materials such as coal, coke, charcoal, and woodchips are used to reduce quartz in submerged-arc furnaces. The process involves a complex set of reactions between solids, gases, and liquids at different temperature levels within the furnace, producing liquid silicon and a process gas containing CO and some SiO. The liquid silicon is tapped at the bottom of the furnace, while the process gas ascends through the charge. The furnaces used are typically open or semi-closed, meaning that the process gas is combusted in air in the furnace hood. This configuration is required to ensure stable operation and to avoid problems with SiO condensation in the off-gas system. However, it has the drawback that valuable CO is oxidised to CO_2 and diluted significantly with air.

1.1 Two-stage silicon production process

Elkem is developing an alternative two-stage silicon production process (Figure 1) in which the overall furnace reactions are separated into two reactor stages:

- One reactor in which silicon carbide (SiC) is produced from quartz and carbon, generating a high-purity CO gas stream.
- One reactor in which silicon is produced from SiC and quartz, with combustion of process gas as in conventional silicon furnaces.

In this configuration, approximately two-thirds of the carbon entering the process is converted to CO in the SiC reactor, while the remaining one-third is emitted as CO_2 from the submerged-arc furnace. A similar process, although without focus on preserving a pure CO gas stream, was previously investigated in the Solsilc project for production of solar-grade silicon (Nygaard, 2008; Kvande, 2011).

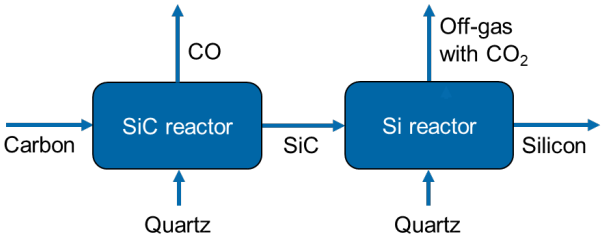

Figure 1: Schematic of the two-stage silicon production process.

The two-stage process offers several potential advantages compared with conventional silicon production:

- The chemical energy in the CO gas is preserved, enabling more efficient utilisation of off-gas carbon. This is a key advantage in the Elkem Sicalo® concept (see Section 1.2).
- The CO gas can be utilised for process heat or electricity generation. In addition, combustion of CO in gas burners or gas engines results in higher CO_2 concentration in the off-gas, which may facilitate more cost-efficient CO_2 capture. Such solutions are being investigated in the manganese industry (Enova, 2023).
- The volumetric flow rate of the off-gas is significantly reduced. For an equivalent carbon throughput, the flow rate of pure CO gas is approximately 5% of that of conventional silicon off-gas, enabling a substantial reduction in off-gas system costs.
- The process provides increased flexibility for plant expansion. Existing furnaces can increase capacity by partially substituting conventional reduction materials with SiC, while new SiC production units can potentially be located in areas with lower electricity cost.
- A fraction of the SiC produced in the first stage can potentially be further upgraded and sold for higher-value applications.
- The process may enable production of high-purity silicon, as demonstrated in the Solsilc project (Nygaard, 2008; Kvande, 2011).
- Separation of the reaction steps enables improved understanding and control of the process and may allow more systematic cost optimisation compared with conventional furnace operation.

1.2 The Elkem Sicalo® concept

The Elkem Sicalo® concept aims to significantly reduce CO_2 emissions from silicon production by closing the carbon loop through reuse of off-gas carbon in the process. In this concept, CO and CO_2 from the off-gas are converted to methane via reaction with hydrogen, followed by methane cracking to produce solid carbon and hydrogen. The solid carbon is agglomerated and reused as a reduction material, while the hydrogen is recycled. In principle, this enables substitution of fossil carbon by hydrogen and electricity. This process is illustrated for conventional furnace technology and two-stage silicon production in Figure 2.

The two-stage silicon production configuration has several advantages compared with the one-stage configuration. By preserving approximately two-thirds of the process carbon as a concentrated CO stream, it can:

- reduce hydrogen consumption by approximately one-third,
- reduce capital and operational costs for CO_2 capture, and
- reduce capital costs of the off-gas and energy recovery systems.

In addition, electrode consumption may be reduced due to the lower specific energy consumption in the silicon furnace.

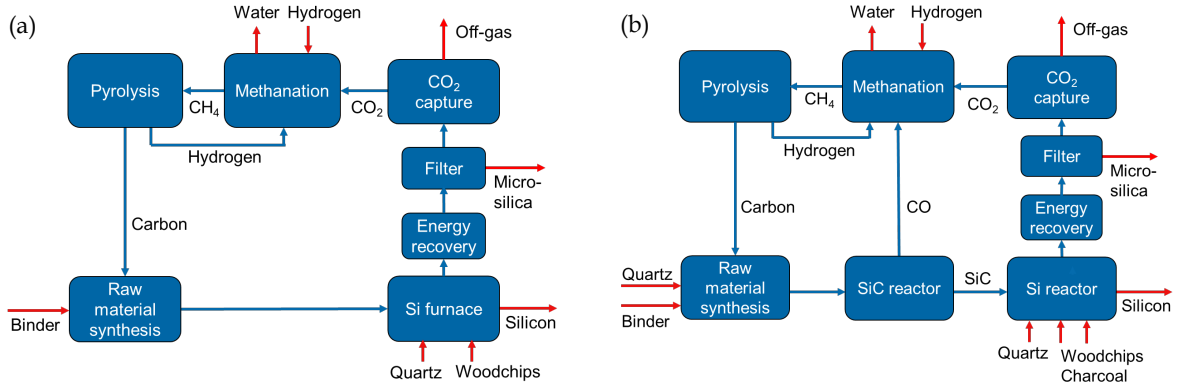

Figure 2: The Sicalo concept. (a) Sicalo one-stage. (b) Sicalo two-stage.

The Sicalo two-stage concept can also be implemented without CO_2 capture, recycling only the CO stream from the SiC reactor. In this case, CO_2 emissions could be reduced by around two-thirds compared with conventional silicon production, while the hydrogen demand would be halved compared with the full two-stage recirculation concept and reduced by around two-thirds compared with the one-stage concept. This provides an alternative with lower emissions reduction, but also lower energy use and lower capital costs per tonne of CO_2 abated.

1.3 Si reactor pilot testing

As part of the development of the two-stage silicon production process, a pilot-scale submerged-arc furnace has been designed and constructed at Elkem's R&D facilities in Kristiansand. It is intended to demonstrate the second stage of the process, namely silicon production using SiC as a reduction material. It also provides a platform for testing other novel raw materials. To date, five campaigns have been conducted with progressively increasing SiC fraction in the reduction material. The primary objective of these campaigns has been to establish an operating strategy for subsequent demonstration campaigns. This paper presents the design of the pilot furnace and selected results together with preliminary analyses from the first five campaigns.

2. THEORY

2.1 Silicon furnace process with conventional reduction materials

In conventional silicon production, the furnace is charged with quartz and carbon-based reduction materials. As these materials enter the furnace, moisture and volatile matter are released from the reduction materials and combusted at the charge top, while fixed carbon and quartz descend through the furnace.

Furnace reactions

In a simplified model, the furnace may be divided into two main zones: one hot inner zone and one slightly cooler outer zone. In the inner zone, SiO_2 reacts with Si to form SiO gas, and the SiO gas reacts with SiC to produce silicon and CO gas.

$$SiO_2(l) + Si(l) = 2\,SiO(g) \qquad \Delta H_{2000\,^\circ C} = 82\ \text{kWh/kmol SiO} \qquad \text{(I)}$$

$$SiO(g) + SiC(s) = 2\,Si(l) + CO(g) \qquad \Delta H_{2000\,^\circ C} = 48\ \text{kWh/kmol SiO} \qquad \text{(II)}$$

This gives the following highly endothermic overall reaction:

$SiO_2(l) + SiC(s) = Si(l) + SiO(g) + CO(g)$ $\Delta H_{2000\,°C}$ = 212 kWh/kmol SiO (III)

The silicon produced is tapped from the bottom of the furnace, while the SiO and CO gases ascend to the outer zone, where SiO gas is recovered mainly through the following two exothermic reactions:

$SiO(g) + 2\,C(s) = SiC(s) + CO(g)$ $\Delta H_{1700\,°C}$ = -21 kWh/kmol SiO (IV)

$2\,SiO(g) = SiO_2(l) + Si(l)$ $\Delta H_{1700\,°C}$ = -84 kWh/kmol SiO (V)

The reaction heat from these reactions heats the descending colder materials. Reaction IV produces SiC, which descends to the inner zone, and CO, while Reaction V produces a mixture of SiO_2 and Si. The CO gas produced in both zones, together with SiO gas not recovered in the outer zone, is combusted together with the volatiles at the charge top.

Efficient SiO recovery in the outer zone is crucial for achieving a high silicon yield. Reaction IV is also essential because it generates SiC, which is required in Reaction II, whereas Reaction V is less desirable because the SiO_2/Si condensate formed may act as a binder between solid particles and reduce gas permeability and impede the descent of materials. Reaction V also generates four times as much heat as Reaction IV, which may give a temperature increase that inhibits both reactions and thereby reduces SiO recovery. Traditionally, considerable emphasis has therefore been placed on selecting reduction materials with appropriate SiO reactivity, to promote Reaction IV rather than Reaction V.

The overall reaction for both the inner and outer charge zones, when using only fixed carbon as a reducing agent and accounting for SiO losses, can be expressed as:

$SiO_2 + (1+\mu)\,C = \mu Si + (1-\mu)\,SiO + (1+\mu)\,CO$ (VI)

where μ is the fraction of silicon units converted from SiO_2 all the way to Si.

Carbon coverage

A key factor when operating the furnace is the carbon coverage, defined as the moles of fixed carbon (fix C) in the reduction materials per mole of oxygen in the quartz fed to the process:

$$FC = \frac{n_{\text{fix C}}}{2 \cdot n_{SiO_2}} \quad [1]$$

The carbon coverage is adjusted to limit SiO losses and at the same time avoid accumulation of carbon in the form of SiC in the furnace.

In practice, some fixed carbon is combusted at the charge top before meeting any SiO gas, while some of the electrode carbon participates in the furnace reactions. The effective carbon coverage is therefore defined as:

$$f_C = \frac{n_{C,rx}}{2 \cdot n_{SiO_2}} = FC - \frac{n_{\text{fixC loss}}}{2 \cdot n_{SiO_2}} + \frac{n_{\text{electrode}}}{2 \cdot n_{SiO_2}} \quad [2]$$

where $n_{C,rx}$ is the number of moles of carbon that participate in the furnace reactions. The effective carbon coverage can also be expressed in terms of μ and calculated based on the SiO loss:

$$f_C = \frac{1+\mu}{2} = \frac{(2n_{SiO_2} - n_{SiO_2,dust})}{2 \cdot n_{SiO_2}} \quad [3]$$

Process performance

The silicon yield and the specific energy consumption are important indicators of furnace performance and operating efficiency. The silicon yield is defined as the silicon tapped divided by the silicon introduced with the raw materials. When only conventional reduction material is used, all silicon enters the process as SiO_2, and the silicon yield is equal to μ and is linearly related to the effective carbon coverage:

$$\text{Si yield} = \mu = 2f_C - 1 \quad [4]$$

The specific energy consumption (SEC) is determined by the furnace thermal efficiency, the silicon yield and operating conditions. The theoretical SEC (ideal operation at 100% thermal efficiency) is given by the enthalpy difference between the input and output material streams. Assuming typical temperatures for the input and output streams, the theoretical energy consumption is around 8.4 MWh/tonne Si when all silicon units are converted (μ = 1). The theoretical SEC as a function of effective carbon coverage for conventional reduction material is shown by the upper black line in Figure 4.

2.2 Silicon furnace process with SiC as reduction material

Replacing part of the carbon in the reduction material with SiC affects the furnace conditions in several ways. Here, SiC is treated as a reduction material because the carbon bound in SiC acts as a reductant in the hot-zone reaction with SiO, while the silicon bound in SiC contributes to the silicon product. The most important changes are:

- The overall reaction is changed such that the overall extent of Reactions I and IV is reduced, resulting in lower specific energy consumption.
- Less carbon is available to capture SiO gas through Reaction IV, so a greater fraction of SiO gas must be captured by Reaction V. This leads to higher heat generation in the outer zone, potentially inhibiting the capture of SiO gas.

By assuming that all SiC is converted to silicon, the new overall reaction for the inner and outer charge zone can be expressed as:

$$SiO_2 + (1 + \mu - n)\ C + n\ SiC = (\mu + n)\ Si + (1 - \mu)\ SiO + (1 + \mu)\ CO \quad \text{(VII)}$$

where n is the number of moles SiC per mole SiO_2 added to the process. The carbon coverage is then equal to:

$$FC = \frac{(n_{fix\ C} + n_{SiC})}{2 \cdot n_{SiO2}} \quad [5]$$

Equations 2 and 3 for effective carbon coverage are still valid, while silicon yield and its relation to effective carbon coverage can be expressed as:

$$\text{Si yield} = \frac{\mu+n}{1+n} = \frac{2f_C-1+n}{1+n} \quad [6]$$

Figure 3 illustrates the expected change in furnace behaviour with increasing SiC content in the reduction material. The figure shows the theoretical SEC as a function of effective carbon coverage for different SiC fractions. The solid black line represents conventional silicon production with carbon as the only reduction material. The coloured lines correspond to 20, 40, 60, and 80 percentage points SiC in the effective carbon coverage, equivalent to n = 0.4, 0.8, 1.2, and 1.6, and illustrate how the SEC decreases with both increasing SiC fraction and increasing effective carbon coverage. Each curve terminates when the effective carbon coverage is fully provided by SiC. Constant-yield lines are shown in grey, illustrating combinations of f_C and SiC fraction that give the same silicon yield. As silicon enters the furnace both as SiO_2 and SiC, the required effective carbon coverage decreases with increasing SiC fraction for a given silicon yield. The objective is to produce silicon with low energy consumption while maintaining high yield. The preferred operating region in the diagram is therefore characterised by high f_C and low SEC.

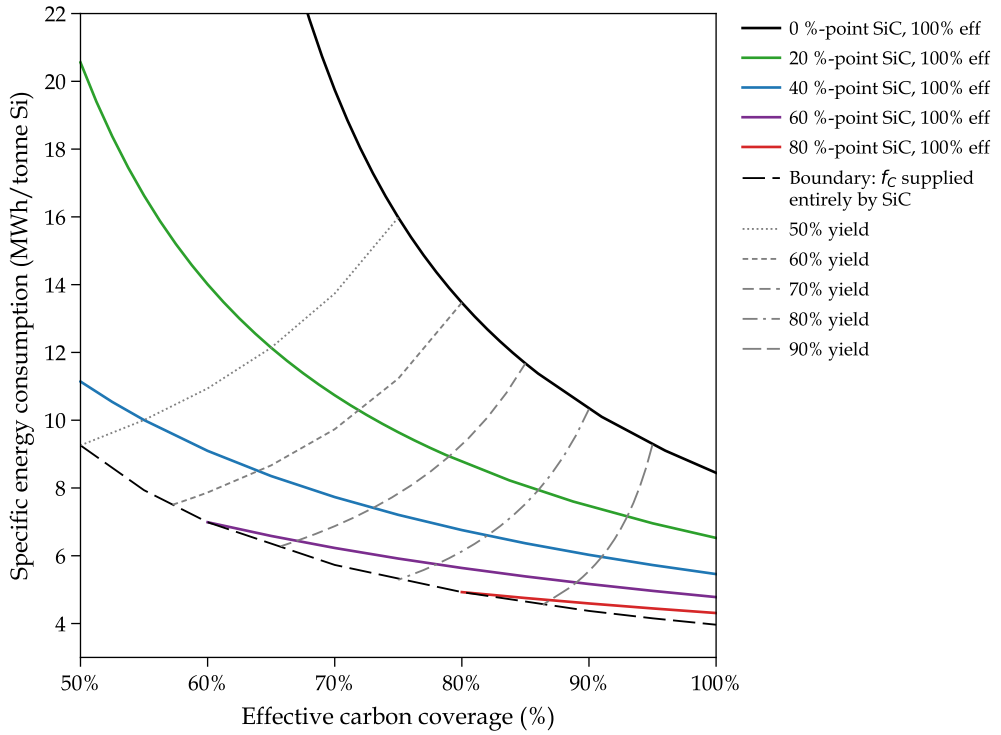

Figure 3: Theoretical specific energy consumption (SEC) as a function of effective carbon coverage (f_C) for different percentage points SiC in f_C. The dashed and dotted grey lines indicate constant yield as a function of f_C and SiC content.

This type of diagram is useful for planning and evaluation of silicon production with a fraction of SiC in the reduction material. For a given furnace load, assumed furnace thermal efficiency, and assumed carbon losses and electrode consumption, charge compositions, weights and charging frequency can be determined. Operational results can be plotted in the diagram and used to guide future furnace operation.

2.3 Previous pilot-scale testing of SiC as reduction material

Pilot-scale campaigns on silicon production with SiC as a reduction material have been conducted previously by several actors. Dow Corning has demonstrated in pilot-scale submerged arc furnace tests (200 kVA) that silicon can be successfully produced with approximately 25% SiC in the reduction material, resulting in significantly reduced energy consumption and increased production rates compared with conventional operation (Dosaj, et al., 1991). Later, the Solsilc project developed a carbothermic reduction route using SiC-

containing agglomerates for production of high-purity silicon, with pilot campaigns carried out up to 1.5 MW scale around 2007–2011, achieving several tonnes of silicon production (Nygaard, 2008; Kvande, 2011; Øvrelid & Pizzini, 2016).

3. THE PILOT SILICON FURNACE

3.1 Furnace design

The pilot silicon furnace, illustrated in Figure 4, is designed and built at Elkem's R&D facilities in Kristiansand to test new raw materials. The furnace power supply consists of a 1.5 MVA single-phase transformer with 32 secondary voltage levels in the range 40–90 V. The maximum electric current to the furnace is 4 kA, limited by the capacity of the electrode and the flexible cables connected between busbars, bus tubes and the water-cooled contact clamp.

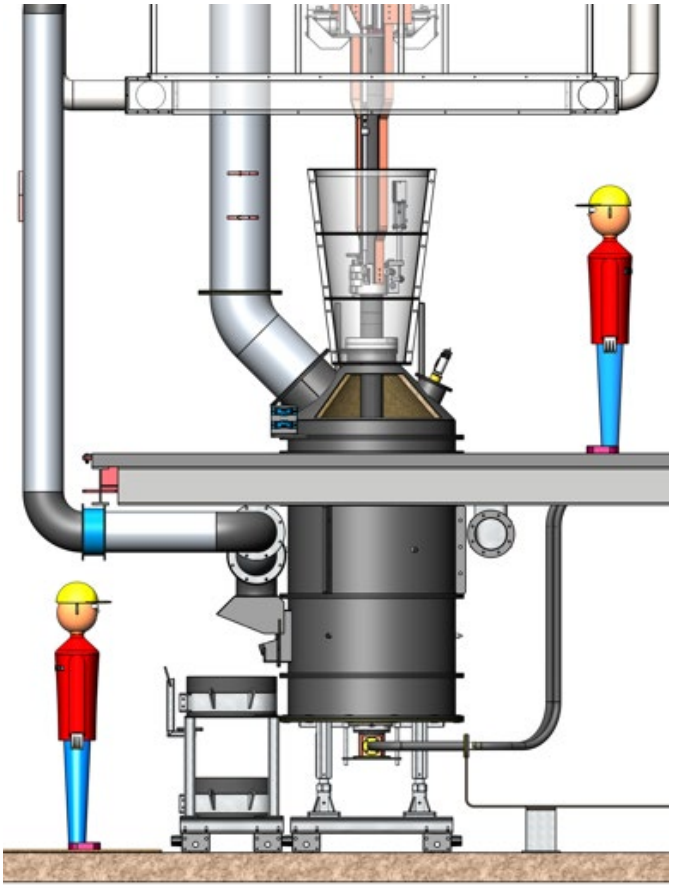

Figure 4: Pilot-scale submerged-arc furnace for silicon production.

The furnace is designed for ergonomic use and built over three levels. The taphole and tapping equipment are located at the bottom level (+6.0 m MSL), the middle level contains the furnace roof hatches for stoking and charging of raw materials (+8.7 m MSL), and the upper level, above the ventilation hood and not shown in the figure, is used for assembly of new electrode elements (+13.4 m MSL). The process chamber is 0.8 m in diameter and 0.7 m high from the bottom to the air intake. The electrode column has a diameter of 15 cm, and the water-cooled bottom contact is attached to a graphite bottom electrode with a diameter of 17.5 cm.

The electrical operating conditions are controlled by setting the voltage level and using a current controller to adjust the electrode column position to maintain the current setpoint. The

campaigns carried out to date have used an electric load of around 130 kW, a transformer secondary voltage level in the range 51–55 V and an electrode current in the range 2.7–3.0 kA.

The process gas leaves the furnace through an off-gas duct with capacity >6000 Nm^3/h. The process gas, the tapping fume and the air from the ventilation hood, which captures fume released from the furnace hatches, are sent to a bag filter with a capacity of 30 000 Nm^3/h.

3.2 Instrumentation and data collection

The measured and registered parameters used for furnace operation, process analysis, and material balance calculations are summarised in Tables I–III.

Table I: Logged parameters for furnace operation and control.

Parameter	Unit	Purpose / comment
Furnace load	kW	Monitoring electrical power input
Current	A	Furnace operation and control
Electrode holder position	mm	Electrode movement and control
Electrode voltage	V	Electrical operating condition
Transformer voltage	V	Transformer operating condition
Voltage harmonics	%	Monitoring electric arc conditions
Current harmonics	%	Monitoring electric arc conditions
Lining temperatures	°C	Thermal monitoring of furnace lining
Furnace overpressure	mmH_2O	Pressure monitoring in the furnace
Off-gas NO_x content	ppm	Indicator of combustion/blowing conditions
Off-gas dust concentration	mg/Nm^3	Indicator of blowing conditions
IR images/videos of charge top	–	Visual monitoring of charge-top conditions, including temperature measurements

Table II: Logged parameters for process analysis.

Parameter	Unit	Purpose / comment
Off-gas composition	vol%	CO_2, CO, H_2, Ar, N_2, O_2
Cooling water flow rates	L/h	Electrode holder
	L/h	Bottom contact
Cooling water inlet and outlet temperatures	°C	Electrode holder
	°C	Bottom contact
Gas flow rates	Nm^3/h	Off-gas duct
	Nm^3/h	Combustion air
Gas temperatures	°C	Off-gas duct
	°C	Combustion air

Table III: Manually measured and registered parameters for material balance.

Category	Parameter	Unit
Input materials	Baking coke bed material	kg
	Charge materials	kg
	Electrode slip	cm
	Electrode consumption/addition	cm
Output materials	Tapped metal	kg
	Filter dust	kg
	Material accumulated in furnace after the campaign	kg

4. PILOT CAMPAIGNS WITH SIC AS REDUCTION MATERIAL

4.1 Pilot campaign overview

The five pilot campaigns are summarised in Table IV, and the corresponding carbon coverage and reduction material mix are shown in Figure 5. The first campaign was carried out using only coke and woodchips, while the SiC content was subsequently increased by around 20 percentage points in each campaign. SiC was introduced in several forms, including 2 mm SiC, SiC briquettes (90 wt% SiC and 10 wt% carbon black or 100 wt% SiC), composite briquettes (1 mol SiO_2/1.5 mol SiC), or SiC agglomerates developed in the Horizon Europe project MECALO. The last two campaigns were both conducted with around 60 percentage points SiC but using different types of SiC agglomerates. The carbon coverage was around 100% in the first three campaigns and was reduced to around 95% in the fourth and fifth campaigns. The duration was four days in the first four campaigns and five days in the final campaign.

Table IV: Pilot campaign overview.

ID	FC	%-points SiC in FC	Length	Comment
0% SiC (#1)	99%	0%	4 days	Reference reduction material.
20% SiC (#2)	100%	20%	4 days	SiC: 50% SiC briquette, 50% 2 mm
40% SiC (#3)	101%	42%	4 days	SiC: 50% SiC briquette, 50% 2 mm
60% SiC comp (#4)	94%	62%	4 days	SiC: 50% SiC briquette, 50% composite briquette
60% SiC MEC (#5)	95%	60%	5 days	SiC: MECALO agglomerate.

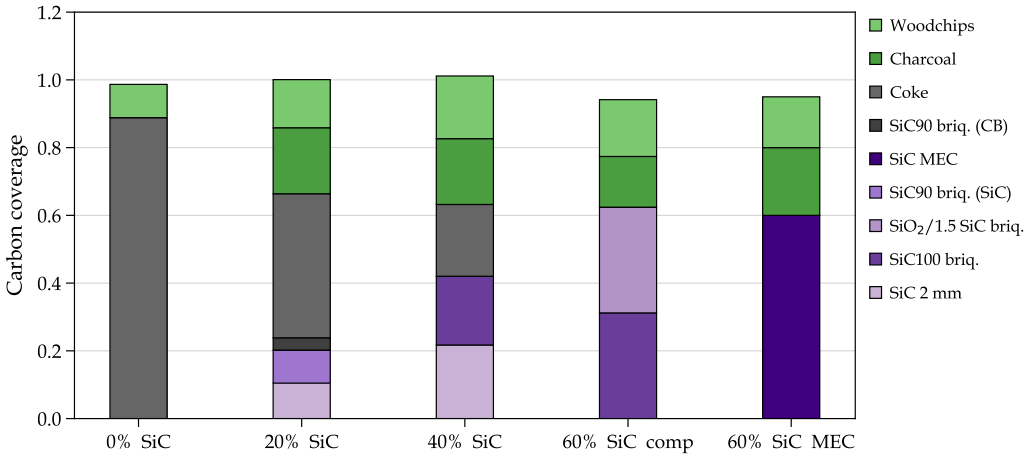

Figure 5: Nominal carbon coverage and SiC contribution in the test charge for the five pilot campaigns.

4.2 Operating procedure

The pilot campaigns consisted of the following operational phases:

1. **Baking (16–24 hours):** Baking of the lining.
2. **Charge filling (8–24 hours):** Gradual filling of the furnace with a start charge, with the aim of achieving stable furnace operation by the end of the period.
3. **Charge transition (8 hours):** Transition to the test charge. At the end of this period, the furnace was assumed to be completely filled with the test charge.
4. **Data collection (48–56 hours):** Stable operation with the test charge and collection of process data.
5. **Termination:** The campaign was terminated 20–30 min after the final tapping and charging, followed by cooling over three days without any mechanical movement.

The furnace was tapped every 60–75 minutes and stoking and charging of raw materials were carried out two to three times during each tapping cycle.

4.3 Material balance

Simplified stoichiometric balances were estimated for the data collection period of each campaign by assuming that (i) the electrode material is pure carbon, (ii) all tapped metal is silicon, (iii) all filter dust is SiO_2, and (iv) the oxygen in the SiO_2 input is converted to either SiO or CO.

Figure 6 illustrates the carbon balances. The carbon input per mole of SiO_2 is shown in the first column and the carbon participating in furnace reactions per mole of SiO_2 is shown in the second column for each campaign. The first column is equal to 2·FC plus the electrode consumption, while the second column is equal to 2·fc, corresponding to the amount of carbon leaving the process as CO gas. The difference between the two columns is the sum of carbon lost due to combustion at the charge top and carbon accumulated in the furnace in the form of SiC. The electrode consumption varies significantly between the campaigns, indicating overcoking and undercoking with low and high electrode consumption, respectively. The ratio of carbon participating in furnace reactions to total carbon input was lower in the first campaign (62%) and then remained relatively constant in the remaining campaigns (71–75%).

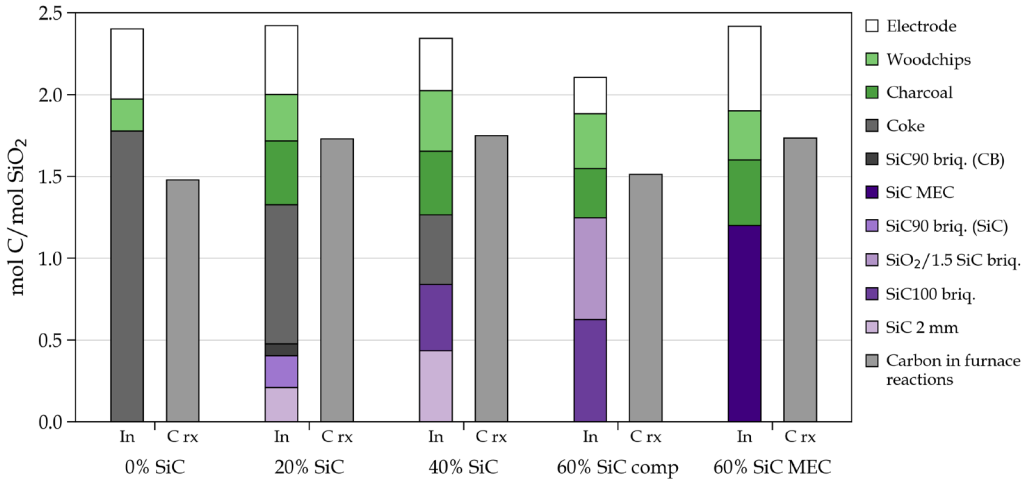

Figure 6: Molar carbon input and carbon participating in furnace reactions per mole of SiO_2 input.

Figure 7 illustrates the silicon balances. The various forms of silicon input per mole of SiO_2 are shown in the first column, while the silicon output in the form of liquid metal and dust is shown in the second column for each campaign. It is evident that in the second, third, and fourth campaigns, less silicon left the furnace than entered, indicating accumulation of silicon in the form of Si or SiC within the furnace. In contrast, the fifth campaign showed slightly higher silicon output than input, indicating that some silicon accumulated in the charge filling and charge transition periods was drained during the data collection period.

Silicon yields estimated on the basis of tapped silicon and on filter dust are presented in Table V. For the third and fourth campaigns, yields based on tapped silicon are significantly lower than those estimated from filter dust, indicating accumulation of silicon inside the furnace.

The first campaign resulted in a very low silicon yield of 48%. At this stage, the stoking and charging procedures were not yet optimised, and breakdowns in dust and NO_x measurements

made it difficult to predict and control blowing. The yields based on dust improved in the second and third campaigns, most likely due to improved stoking and charging procedures. In the fourth campaign, the dust-based yield decreased, before increasing again in the fifth campaign.

The increasing accumulation of silicon in the furnace from the second to the fourth campaign led to a stronger focus on tapping and draining performance. The fifth campaign was therefore extended by one day and included a longer charge-filling period to establish stable tapping conditions before switching to the test charge. Additional emphasis was also placed on maintaining high temperatures in the lower part of the charge. The fifth campaign achieved a high silicon yield: 92% based on tapped metal and 88% based on dust.

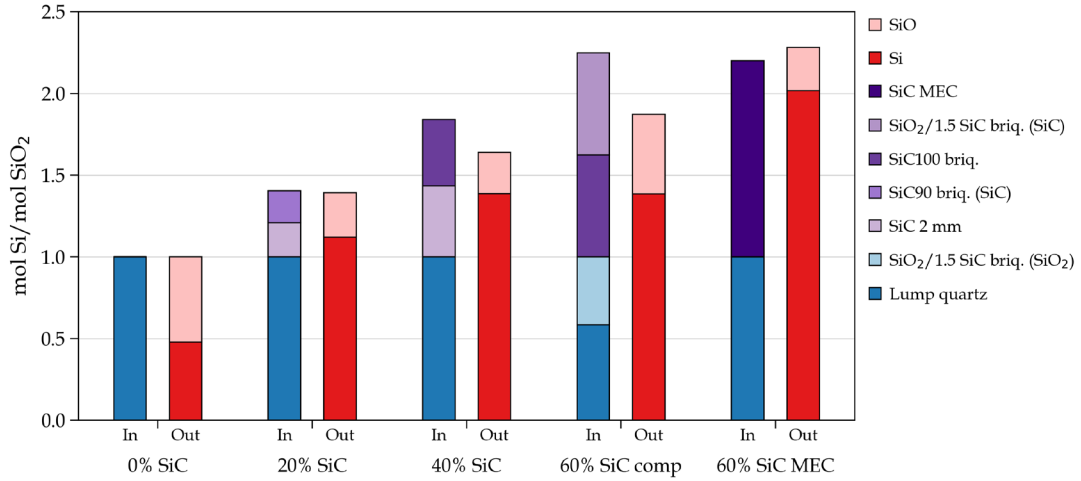

Figure 7: Molar silicon input and output per mole of SiO_2 input.

Table V: Estimated silicon yields.

Estimate basis	0% SiC (#1)	20% SiC (#2)	40% SiC (#3)	60% SiC comp (#4)	60% SiC MEC (#5)
Silicon tapped	48%	80%	75%	62%	92%
Filter dust	48%	81%	86%	78%	88%

4.4 Furnace excavation

After the termination of each campaign, the furnace was excavated, the cavities were measured, and the different types of materials were mapped and weighed. A certain amount of silicon material containing a mixture of Si and SiC (Si·SiC) is expected and was observed after all campaigns. The approximate mass of Si·SiC materials in the furnace is summarised in Table VI. The amount increased from 36 kg after the reference campaign to 135 kg after the fourth campaign, before decreasing to 37 kg after the fifth campaign. This is consistent with the material-balance observations and indicates that improved tapping and draining conditions in the fifth campaign substantially reduced the amount of material retained in the furnace.

Table VI: Approximate mass of Si·SiC material in the furnace after each campaign.

Quantity	0% SiC (#1)	20% SiC (#2)	40% SiC (#3)	60% SiC comp (#4)	60% SiC MEC (#5)
Mass of Si·SiC	36 kg	70 kg	87 kg	135 kg	37 kg

An illustration of the cavity mapped after the fifth campaign is given in Figure 8. The cavity was oval, with diameters of approximately 50 cm in the east–west direction and 25 cm in the north–south direction. The accumulation of Si·SiC was higher on the north and south sides of the furnace. This is likely related to the location of the two stoking and charging hatches in the east and west and suggests that the stoking and charging procedures can be further optimised to obtain more favourable cavity conditions.

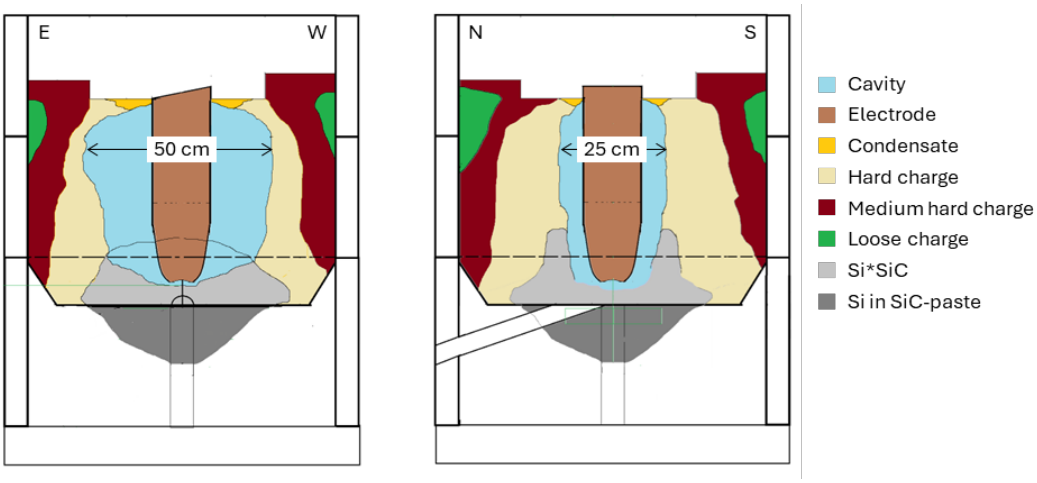

Figure 8: Illustration of the cavity mapped during excavation of the furnace after the fifth campaign. The left figure shows the cross section from east to west, and the right figure shows the cross section from north to south.

4.5 Specific energy consumption

The specific energy consumption and thermal efficiencies of the furnace during the five campaigns are presented in Table VII. The thermal efficiency of the furnace was around 50% during the first three campaigns, with a drop to 43% and 45% for the fourth and fifth campaigns. The lower value in the fourth campaign can be explained by the lower silicon yield, whereas for the fifth campaign the reason may be higher thermal losses associated with higher temperatures in the tapping zone. Thermal efficiencies in the range of 40–50% are as expected for pilot furnaces of this size.

Table VII: Specific energy consumption (SEC) and furnace thermal efficiency for the five campaigns.

Metric	**0% SiC (#1)**	**20% SiC (#2)**	**40% SiC (#3)**	**60% SiC comp (#4)**	**60% SiC MEC (#5)**
SEC (MWh/tonne)	34.0	16.4	12.6	13.8	11.8
Furnace thermal efficiency	49%	48%	49%	43%	45%

Figure 9 shows SEC as a function of effective carbon coverage at 50% thermal efficiency for varying amounts of SiC in the reduction material, with the five campaigns plotted. The colours of the dots indicate SiC content and are consistent with those of the lines. The first three campaigns are close to the theoretical curves calculated for 50% furnace thermal efficiency, whereas campaigns #4 and #5 plot above the corresponding curves because their measured thermal efficiencies were lower than 50%, at 43% and 45%, respectively.

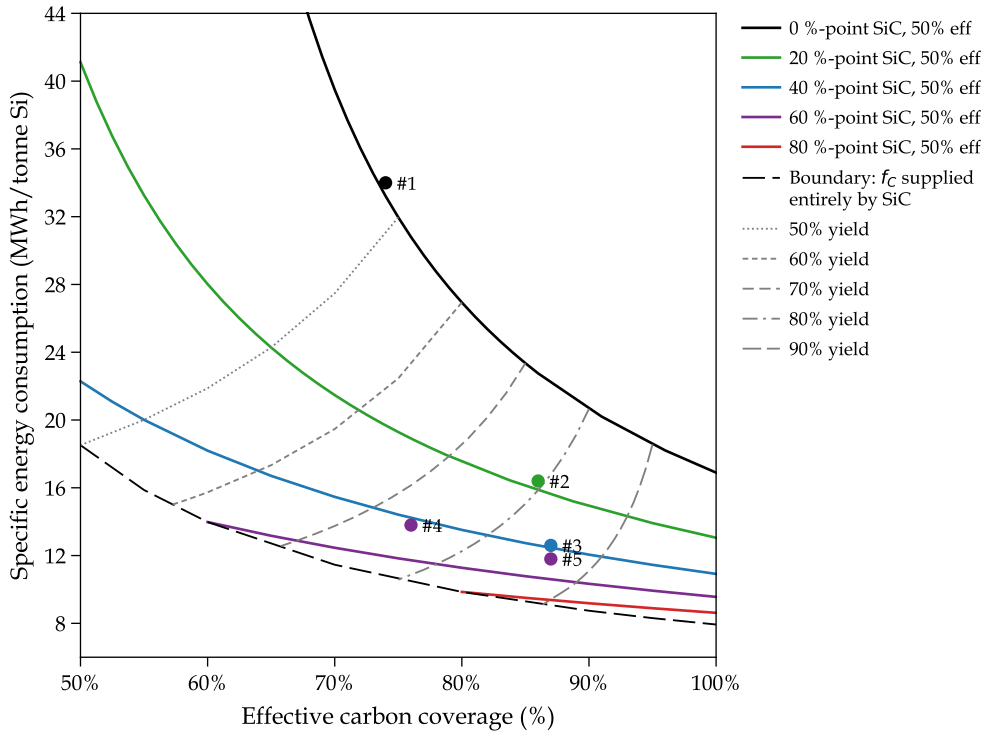

Figure 9: Measured specific energy consumption for the five pilot campaigns compared with theoretical SEC curves calculated at 50% furnace thermal efficiency as a function of effective carbon coverage and SiC contribution. Grey lines indicate constant calculated silicon yield.

5. CONCLUSION

This work presents the design of a pilot-scale submerged-arc furnace and results from five pilot campaigns carried out to establish an operating strategy for silicon production with a high SiC fraction in the reduction material. The campaigns were performed with progressively increasing SiC fractions, ranging from a reference case without SiC to approximately 60 percentage points SiC in the carbon coverage. The best campaign achieved a silicon yield of 92% based on tapped metal and 88% based on filter dust, with a specific energy consumption of 11.8 MWh per tonne Si. The results provide an experimental basis for subsequent demonstration campaigns and further development of the two-stage silicon production process and the Elkem Sicalo® concept.

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