Tapping of metallurgical silicon furnaces – a brief comparison between continuous and discontinuous processes

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Abstract – The efficiency of the standard carbothermic reduction process for producing f metallurgical silicon in submerged arc furnace is highly dependent of the tapping process. The liquid metalloid generated at high temperatures in the furnace hearth needs to be tapped from the crucible in such a way that the upstream processes are not affected (*i.e.* stoking process in the top of the furnace, instability of the electrical conditions in the reaction zones, and electrode positions in the charge). There are two basic processes that are used in this industry with proven results and good efficiencies: continuous and discontinuous tapping. The aim of this article is to compare the advantages and disadvantages of these two tapping processes for metallurgical silicon furnaces and provide some guidance for the new entrants, during the process engineering design for greenfield projects, and also to share with operators some important aspects to be considered in their actual operations or eventual Brownfield expansions. The authors will explore different aspects like process control, thermal efficiency of the equipment, silicon recovery, slag generation, losses in the process, environmental emissions and operational complexity, safety risk assessment, and engineering details that allow higher efficiencies to be attained in both cases. The general idea is to provide sufficient information to be used in decision-making, improvement analysis, or optimization of existing operations, expansions, or new projects.

Keywords: Silicon production, continuous/discontinuous tapping, slag viscosity, environmental emissions, thermal efficiency, silicon recovery.

INTRODUCTION

In silicon production, electricity is fundamental to the reduction process. The overall reaction for the silicon process is the following:

$SiO_{2\,(s)} + 2C_{(s)} \rightarrow Si_{(l)} + CO_{(g)}$ (T > 2000°C) [1]

The reaction requires a considerable input of electrical energy to occur, which is brought to the reaction zone through the electrodes. The typical path of the electricity is shown in Figure 1.

Figure 1. Overview of the process path of the electricity until the reaction zone (Viridi.iQ GbmH).

Figure 2 shows a schematic of the silicon production process, with the emphasis on the importance of the electrodes and tapping process.

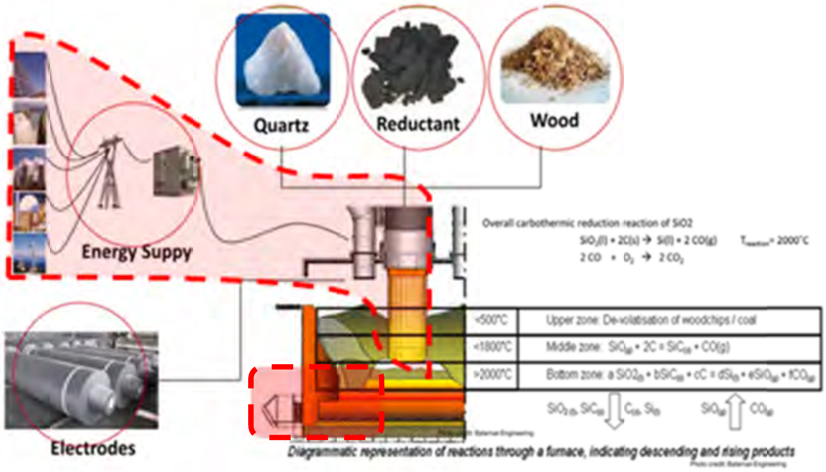

Figure 2. *Typical raw materials and electricity path through electrodes in Si process (Viridis.iQ GmbH).*

During the production process, the main reactions occur in different zones in the furnace crucible, as illustrated in Figure 3.

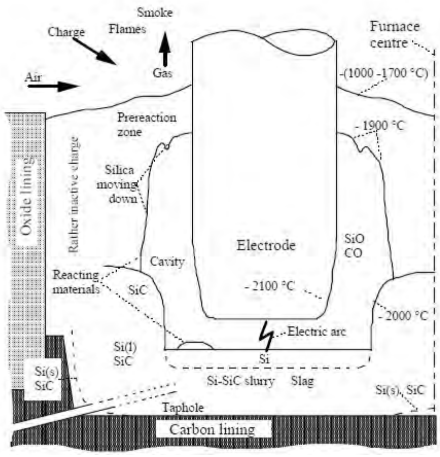

Figure 3. Distribution of phases and elements inside a silicon furnace. Liquid silicon in contact with carbon or SiO2 may react and lower the productivity of the furnace, impacting the tapping process (Schei, Tuset, and Tveit, 1998).

The general reactions are shown in Figure 4.

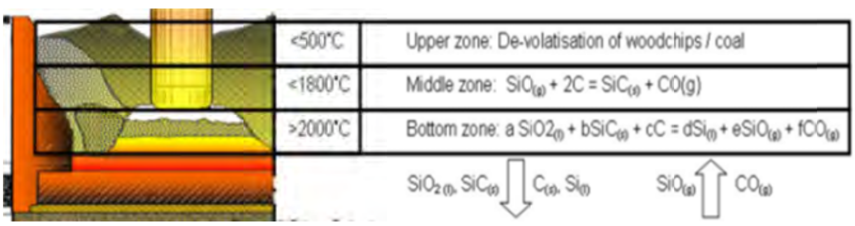

Figure 4. Diagrammatic view - reactions in a submerged arc furnace for silicon production (Bateman Engineering).

Under the standard operational conditions, the liquid silicon is produced mostly in the lower part of furnace hearth, termed the lower reaction zone, above 2000°C (Schei, Tuset, and Tveit, 1998). These high temperatures are achieved due to the electrical arc and the balance between the most exothermic reactions occurring inside the furnace. The main products, as shown in Figure 3, are silicon metal and slag in the liquid state.

Based on measurements in different furnaces worldwide, where the author has worked in the past 30 years, the tapped temperature of this mix of liquid silicon and slag is normally[1] in the range of 1600–1650°C. These temperatures can vary by about ±2%, depending on the process and the operational conditions of electrodes length and useful furnace area available. While the tap-hole is open , depending on the furnace operating conditions, some gases (mostly SiO gas and CO gas) at higher temperatures (>1800°C)[2] and high speed (up to 65 m/s)[3] will be expelled during the tapping process. In some cases, the tapping stream may contain unreacted material and slurry containing some SiC, but these instances would not occur during normal operation.

Figure 5 shows where the process take place, inside the furnace towards the tap-hole, till the refractory ladle (liquid material) and the tap-hole chapel; also called the secondary de-dusting system. Although some plants do not collect those gases, a gas extraction system is important to minimize the general gas emissions in the post-tapping area, within the main furnace building.

Figure 5. Cross-section of tap- hole and furnace hearth. The ladle, shell, furnace platform, and tapping tools are also depicted (Viridis.iQ GmbH).

In the bottom of the furnace hearth, the liquid silicon (brighter material) is produced in the lower reaction zone at high temperatures and flows through the tap-hole into the refractory ladles with capacities[4] up to 10 t. For this specific paper, the author considered as base case scenario a submerged arc furnace with an active power of 24 MW.

The main targets that furnace operators should consider at this stage are the following:

- Guarantee all safety and environmental conditions in the tapping area (including cleanness and availability of the tools in the best condition).
- Usage of the best standard operational procedures in order to avoid clogging of the tap-hole by materials generated inside the furnace (this could lead to loss of production, due mainly to the accumulation of liquid silicon inside the furnace which result in liquid silicon coming into contact with quartz at high temperatures, producing silicon monoxide according to the following back-reaction:

$$Si_{(l)} + SiO2_{(s)} \rightarrow 2SiO_{(g)} \ (>1800°C) \qquad [1]$$

[1] Viridis.iQ GmbH Metallurgy and Engineering thermodynamic simulations.
[2] Viridis.iQ GmbH Metallurgy & Engineering estimates
[3] Reference: measurements done at Elkem plant published in Tveit, et all paper in 1992 – "The Tapping process" – NTNU Conference paper.
[4] Viridis.iQ GmbH Metallurgy & Engineering project design

Over time, the accumulated silicon may also react with carbon and hence disturb electrical conditions in the reaction zones, leading to instability of electrode positions and high volumes of gas (blows) on top of the furnace. These conditions will also significantly increase the temperature on the top of the furnace, putting the operation and equipment at risk.

- During operation, be assured of the dimensional integrity of the tap-hole, and the best usage of the main tools used during the tapping procedure.
- Avoid potential cross-contamination (most likely by iron) during the tapping process, caused mostly by incorrect usage of the steel tools during tapping.
- Carry out important support and control procedures during tapping (level of liquid silicon into the refractory ladle, thermal control between 1500 and 1700°C, based on the author's experience), liquid silicon sampling, *etc.*).
- Evaluate and maintain all equipment and tools in this area and the post-tapping area (platform position and conditions, tapping stinger, mud gun, secondary de-dusting valves and the chapel, tap-hole refractories, as well as the carbon blocks) as a preventative action.

Problems related to the tapping process will affect furnace performance and in general also the stoking and control room operations. Quality and environmental problems could also arise due to improper tapping operation. The tapping area is one of the most risky areas for operators and safety procedures and condition of equipment MUST to be observed to avoid any injuries or accidents.

Based on the author's experience in silicon operations worldwide, good tapping procedures will help to obtain optimum silicon yields in the process. The tapping process includes direct costs and hence influences the overall operational expenditures of the plant.

Tapping in silicon operations normally is done continuously, keeping the tap-hole constantly open and exchanging the ladles time to time based on the tapping cycle.

In a discontinuous tapping process, the tap-hole is open for a certain period of time and closed at the end of that cycle. Table 1 is a simplistic qualitative overview of the pros and cons of continuous and discontinuous tapping of silicon furnaces.

Table 1 *Comparison (qualitative) on continuous and discontinuous tapping.*

Item	Continuous tapping	Discontinuous tapping
Stoichiometry	+++	+
Thermal stability	+	+++
Electrical stability	+++	+
Environmental emissions	+	+++
Tapping consumables	+++	+
Labour intensity	+	+++
Cross-contamination (quality)	+++	+

For continuous tapping the stoichiometric balance inside the furnace is favourable, due to the lower risk of reverse reaction; this also impacts positively o the electrical stability due to the lower risk of liquid metalloid accumulation inside the crucible. Since the frequency of opening and closing of the tap-hole is much lower than with discontinuous tapping, much fewer consumables are needed. The risk of quality cross-contamination is also lower.

With discontinuous tapping, thermal stability is more easily attained, due to the fact that during the part of the cycle while the furnace is closed, the liquid silicon is accumulated and the reaction zone loses no energy through the tap-hole. Keeping the furnace closed during the discontinuous tapping cycle will also reduce the environmental emissions.

In terms of labour intensity, discontinuous tapping has an advantage due to the fact that during the part of the cycle while furnace is closed the furnace operators (tappers) are not required to work specifically in this region.

A general aggregated *versus* non-aggregated value for both cycles is presented in the next section.

Nowadays, there are several silicon operators that are using continuous casting in their operations, for example the Ferroglobe furnaces in the USA, Europe, and South Africa; Brazilian producers such as RIMA, Liasa, and Minas Ligas; and RW Silicon in Germany (AMG Group). On other hand, a few producers in the Western world are using the discontinuous tapping process; *i.e.* Mississippi Silicon and PCC Bakki will implement the discontinuous tapping process. In the Eastern world, most of the Chinese operators and SIMCOA (Australia) are running their furnaces with discontinuous tapping. SIMCOA utilizes discontinuous tapping most of the time and a continuous regime part of the time.

GENERAL ANALYSIS OF THE TWO ROUTES IN AN ESTABLISHED BASE CASE SCENARIO

In this section, a base case scenario is presented and used as premise for a brief comparison between continuous and discontinuous tapping. All the advantages and disadvantages described here are related to that specific case.

In general, the ideal tapping process needs to be carefully evaluated case by case for an optimum decision in terms of results to be achieved. The type of equipment, raw materials used in the process, skills level of the operational staff, as well as the post-tapping layout area are fundamental considerations in this analysis.

The base case scenario is a 24 MW, 33 MVA furnace operating with three monophasic oil-forced-water-forced (OFWF) transformers, with separate tapchangers for the different levels of electrical parameters that the furnace is operated at. The electrode diameter is 1272 mm (50 inches) and is considered an alternative electrode technology to Södeberg paste.

The pitch circle diameter (PCD) used for the analysis was 3050 mm and furnace hearth dimensions 6900 mm (bottom diameter) and 3200 mm (total height). The secondary operation range was 76–84 kA, and the active power range between 23 and 24 MW. The range C3 Westly factor was 9.6 to 10.2 and the operational resistance 1.1 to 1.2 mΩ.

The optimum distance between the bottom of the crucible (hearth) and the tip of electrode recommended by the author as a key operational parameter was 400 mm. The mass balance considered was 108% (with 8% of excess carbon considering the stoichiometric balance of the overall reaction (Equation [1]).

The raw material considered in the reaction zone is depicted schematically in Figure 6 (carbon source: 50% from charcoal, 30% from low-ash coal, 20% from woodchips) –

excess from low-ash coal addition in the normal feeding and batching process (+8% of carbon).

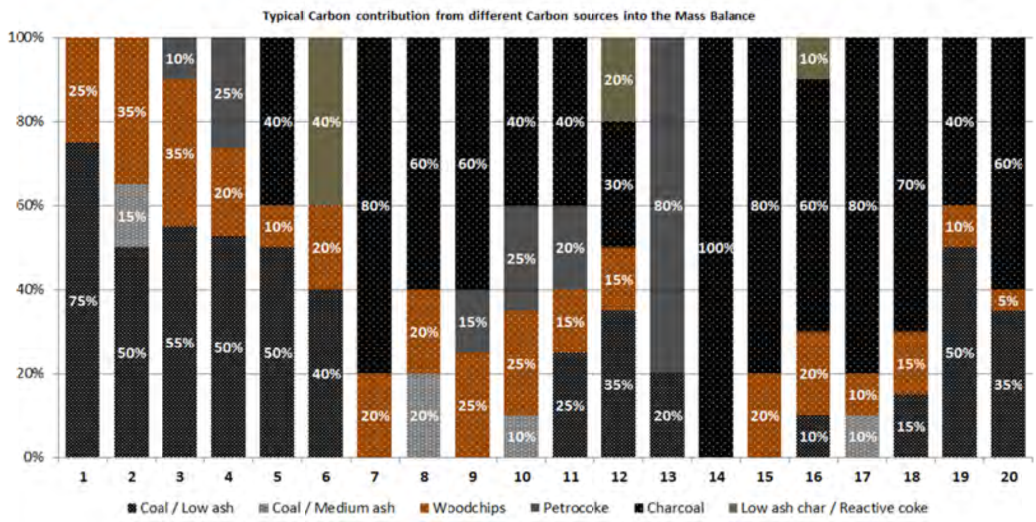

Figure 6. Reducing agents usage in silicon and FeSi furnaces worldwide (Myrvågnes, 2008; updated with V.D.Oliveira benchmarking data, 2013).

Based on the scenario defined, the energy consumption considered in these estimates was 11 232 kWh/t of silicon (considering a silicon recovery and thermal efficiency of process equipment of 90% and 80% respectively, as shown in Figure 7).

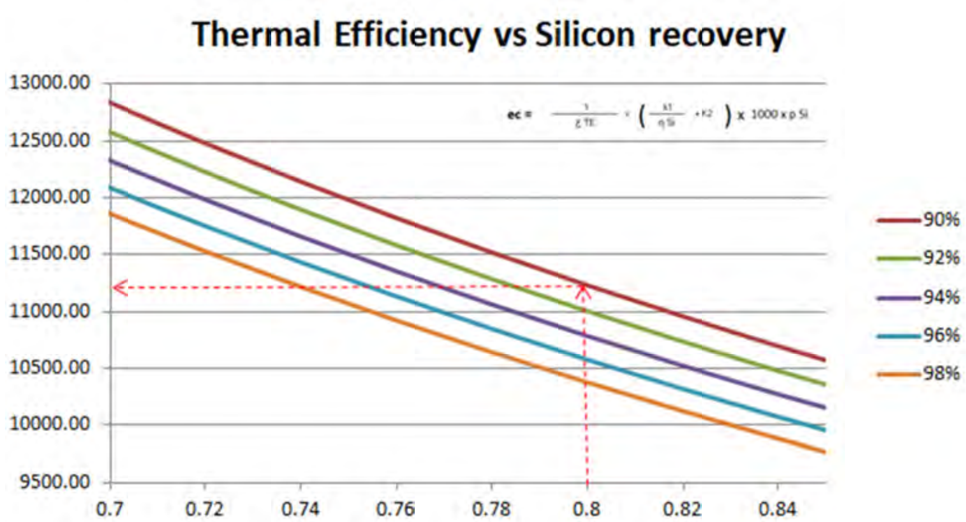

Figure 7. Silicon recovery vs thermal efficiency in metallurgical silicon manufacturing process (Schei, et all, 1998).

Based on the parameters mentioned above, the author determined the volume of liquid silicon produced in the reaction zone at 2000°C:

$$\boldsymbol{Si\ output} = \frac{\mathbf{PW \times t \times Utilization}}{\mathbf{e.c. \times 1{,}000}} \quad [2]$$

where:

Si output = hourly production (t/h)
PW =Active power (MW) – considered 23.33 MW (PW=ficos0.707×App.power33MVA)
t = Time (h) – considered 1 h (hourly production)
Utilization=%timeinoperation (1 – %downtime) – considered 100% (hourly production)
e.c. = Energy consumption (kWh/t) – calculated based on Shei, Tuset, and Tveit (1998) (Figure 6) 11.232 MWh/t.

Based on these parameters, the calculated hourly production of the reference submerged arc furnace is approximately 2.077 t of silicon.

Considering the stationary product generation in normal conditions in the reaction zone, as well as the temperature of 2000°C; is possible to calculate the liquid silicon density inside the furnace. This data will be important in determining the metalloid static height increase due to silicon accumulation inside the furnace. Considering the liquid silicon density as a function of temperature:

$$\boldsymbol{\rho}\ \textbf{Si liquid}\ (\textbf{1700 K to 3000 K}) = \mathbf{2.54 - 2.19}\ \boldsymbol{x}\ \mathbf{10^{-5}}\boldsymbol{T} - \mathbf{1.21}\ \boldsymbol{x}\ \mathbf{10^{-8}}\boldsymbol{T}^{\mathbf{2}} \qquad [3]$$

the densities of the tapped liquid silicon (t) (1650°C) and reduced silicon (r) inside the hearth (2000°C) are respectively ρSi(t) = 2.453 g/cm^3 and ρSi(r) = 2.427 g/cm^3. In terms of silicon accumulation, 0.855 m^3/h accumulation inside the furnace hearth and 0.847 m^3/h for the tapping process are used.

The furnace hearth volume, for didactic purposes was calculated based on three different diameters (referring to the upper, middle, and lower reaction zones. It is important to mention that this is very dynamic parameter and depending on the operation of the furnace, these reactions zones could be mixed and disturbed along the furnace crucible hearth. The premises are based on a design project for a 33 MVA submerged arc furnace for silicon production (Figure 8).

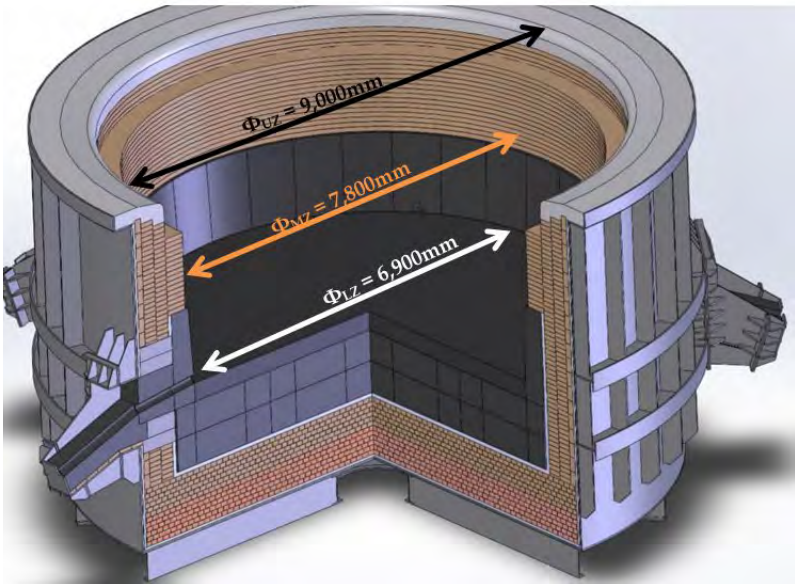

Figure 8. Schematic view of a submerged arc furnace shell used as a base case scenario (Viridis.iQ GmbH).

Table 2 summarize the dimensions of the upper, middle, and lower reaction zones, considered for the useful volume calculation (n = U, M or L):

Table 2 *Dimensions considered for utile volume calculation.*

Reaction zone	Diameter (Φ nZ)	Height (h nZ) – from bottom to the top cumulative
UZ (upper reaction zone)	9000 mm	3200 mm
MZ (middle reaction zone)	7800 mm	2800 mm
LZ (lower reaction zone)	6900 mm	1000 mm

Based on previous studies (including technical papers and excavation works done in several plants in Norway), in normal operations is appropriate to target the tip electrode position close to the hearth bottom, at 0.3 m. The graphs in Figure 9 show the reasons for that aim.

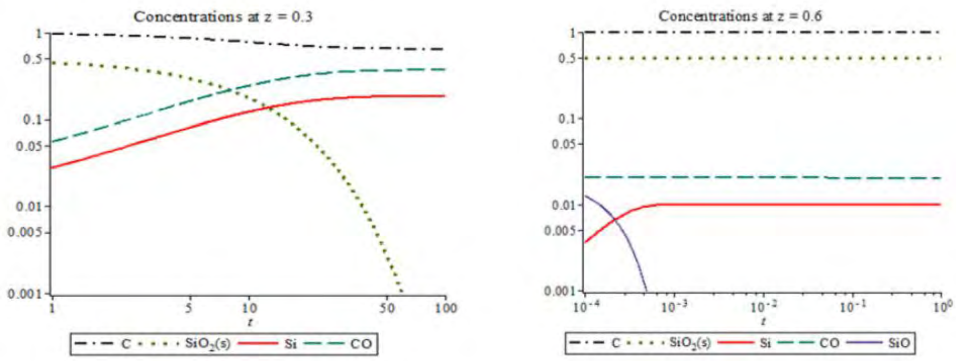

Figure 9. (a) Representative behaviour for the bottom region (0.3 m) and (b) for the top region (0.6 m).

Based also in some references and image analysis, the operational useful volume considered by the author is in the range of 10 to 20% of the design useful volume.

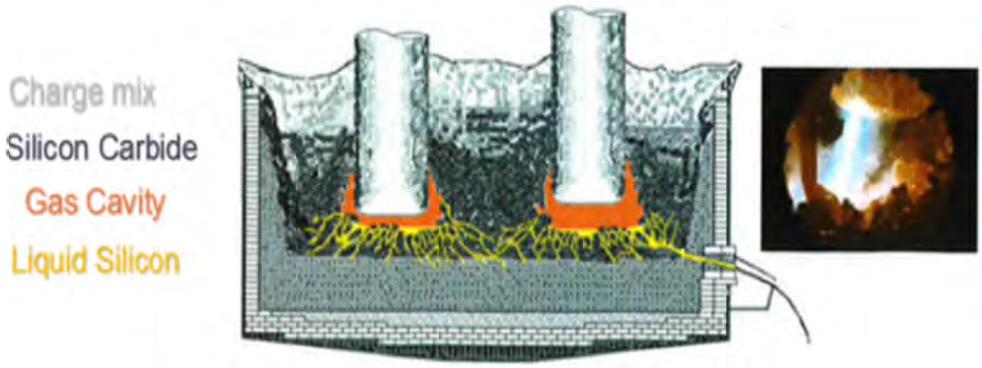

Figure 10. Schematic of a silicon furnace and photograph of crust build-up around gas cavity (Elkem report).

This represents normal conditions of this actual base case scenario here described, considering the operational furnaces conditions and previously calculated parameters of the density of silicon, approximately 2 hours (1.98 hours) of liquid silicon production, until the silicon inside the hearth accumulates to a height where the 'reverse reaction' shown in Equation [2] starts to take place.

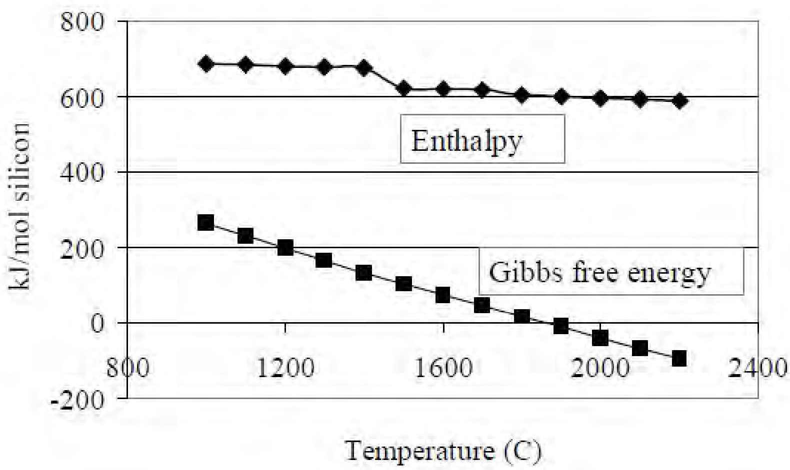

Figure 11. Thermodynamic parameters of the reverse reaction.

The enthalpy[5] and Gibbs free energy[6] related to the reverse reaction (Equation [2]) (Figure 11) confirm that above 1800°C liquid silicon can react endothermically with liquid SiO_2; this represents 6 kWh endothermic consumption and 1.6 Nm^3 of $SiO_{(g)}$ per kilogram of silicon converted via the reverse reaction.

From the process standpoint, the difference between continuous and discontinuous tapping is that the cycles of discontinuous tapping must to be carefully handled once the accumulation of material inside the furnace (liquid silicon) reaches a level where losses of silicon due to the backwards reaction will occur. For continuous tapping, this risk is much lower, since the level of accumulation is considerably smaller.

Based on a mass and energy balance study (Kamfjord, 2012), the energy streams from the tapping area of a similar furnace for silicon production were used as reference for this analysis:

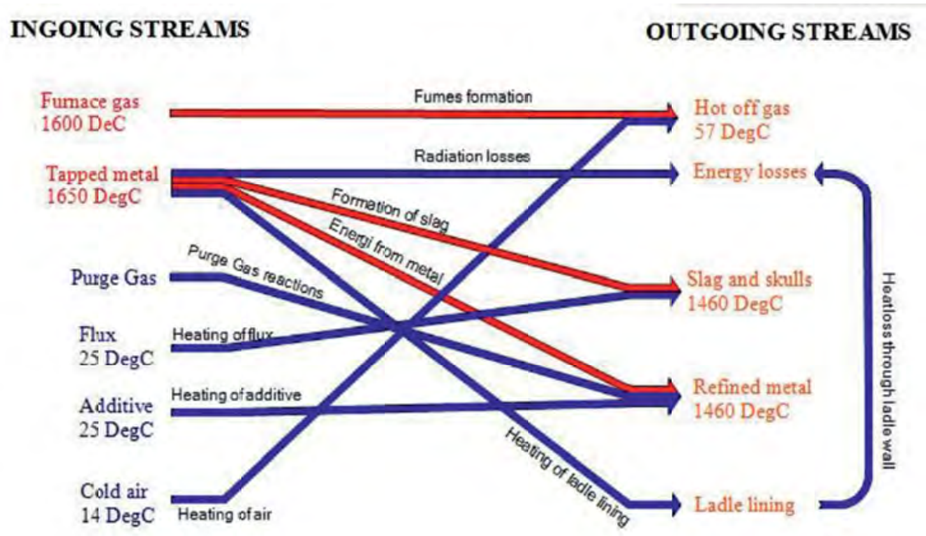

Figure 12. The energy streams in the tapping area (Kamfjord, 2012).

The correlated energy outputs to the tapping area were calculated considering the SiO and CO gas flows into the tapping process.

The energy loss calculation considered the diffusion flux of the main species (CO, SiO, slag, and Si), heat losses, species enthalpy, and effective conductivity.

The estimated loss based on the tap-hole design and process base case scenario is 591 kJ/s (or 591 KW) distributed between radiation (51%), air convection (27%), purge gas (14%), and heating flux (8%).

This data is important for comparing the energy losses between the two tapping methods in metallurgical silicon production.

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[5] The enthalpy of a system is equal to the system's internal energy plus the product of its pressure and volume

[6] The Gibbs free energy is a thermodynamic potential that can be used to calculate the maximum of reversible work that may be performed by a thermodynamic system at a constant temperature and pressure (isothermal, isobaric).

Table 2l.- Times simulation for the three tapping cycles (estimates for the base case scenario).

In order to evaluate the production steps of these two tapping methods, the author used as reference the tapping cycles shown in Table 2I.

Table 3 - *Tapping cycles parametrized (comparison discontinuous vs continuous)*

Tapping cycles	Continuous tapping time (min)	Tasks	Discontinuous tapping time (min)
Tapping cycle 1	0	Opening the tapping hole	5
	125	Tapping cycle 1 DT	30
	0	Closing the tapping hole	5
	0	Tapping hole closed	90
	5	Changing ladles	0
Tapping cycle 2	0	Opening the tapping hole	5
	125	Tapping cycle 2 DT	30
	0	Closing the tapping hole	5
	0	Tapping hole closed	90
	5	Changing ladles	0
Tapping cycle 3	0	Opening the tapping hole	5
	125	Tapping cycle 2 DT	30
	0	Closing the tapping hole	5
	0	Tapping hole closed	90
	5	Changing ladles	0
	390	**Total Time**	**390**
Total productior	**13501**	tons during the 3 cycles	**13501**
Production Flow	tons		tons

To achieve an impartial analysis, the author started from the point that both process are supposedly similar in terms of overall equipment efficiency and the silicon yield is considered the same. On the one hand, the reverse reaction could impact negatively on a furnace that runs under the discontinuous tapping regime; on other hand the heat losses from furnaces running with continuous tapping could be slightly higher, negatively impacting the silicon yield recovery for those furnaces, for example.

Considering the three tapping cycles for a similar furnace, the initial aggregated and non-aggregated values for both cycles are quite different. In the case of continuous tapping, the activities considered as aggregated value for the stream mapping process are at a level of 96%, while for discontinuous tapping, this value is only 23% of the aggregated value activities in that value stream mapping.

This difference is compensated by the liquid flow of silicon during both regimes. Considering the same performance, for continuous tapping the average flow is 36.01 kg/min and during discontinuous tapping the average is 90 kg/min. It is crucial to mention that these averages will oscillate, mostly for discontinuous tapping where in the beginning of the tapping cycle the flow is substantially higher than the average and at the end of the process is lower than the average. These oscillations shows much lower amplitude for continuous tapping, because the furnace is kept open all the time.

From the safety standpoint, this high oscillation is a risk for the operation due to the high volume of liquid hot metalloid (silicon) and liquid slag that must be handled. It is important to mention that the base case scenario was considered to incorporate a moveable furnace operator platform with proper refractory walls and metallic mirror protection. Nonetheless, higher volumes of liquid silicon lead to a higher operational risk that needs to be mitigated by appropriate operational standard procedures, handbooks, and visual control.

sAnother important point related to the process is the heat exchange correlated to continuous and discontinuous tapping. Considering the tap-hole design for the base case scenario with an inclination of 6 degrees (internally) and 15 degrees (in the tap lip) and a tap-hole 150 mm in diameter, the total energy lost per minute in the base case scenario, based on the author's calculations, is around 591 kWh.

Considering that for continuous tapping the furnace is open during all the time used in the calculus basis (390 minutes – Table 2I) while for discontinuous tapping the tap-hole is open for 90 minutes, the estimated losses in the base case scenario are quite different. While for discontinuous tapping the energy loss on tapping is 0.6%, in continuous tapping the loss could reach up to 2.5%. Considering also the higher risk of the reverse reaction in discontinuous tapping, this will contribute significantly to the risk of blows on top of the furnace in the stoking area (1.6 Nm^3 SiO gas per kilogram of silicon converted back to SiO (Kamfjord, 2012); this would lead to higher temperatures in the stoking area and a higher volume of gases in the primary de-dusting system. The situation described above could also impact negatively on the electrical conditions inside the furnace hearth, causing considerable difficulty in maintaining electrode penetration into the submerged positions in the charge.

In terms of consumables, in the short term, discontinuous tapping will result in higher consumption of tap-hole clays and an increase in tapping mouth maintenance and repairs, which will increase maintenance costs because of the much more frequent processes set-ups (opening and closing of tap-holes). In continuous tapping, on the other hand, the consumption of the tapping stinger is higher. The risk of mushroom formation inside the tapping channel is greater for discontinuous tapping. Therefore, from this perspective the continuous tapping regime has a slight economical advantage.

The skills level of operational staff is a fundamental factor for this analysis. Although discontinuous tapping requires fewer operational staff in the tapping area (most likely, the tappers), the furnace control operators (controllers) are required to have much higher skills to operate the furnace due to the greater electrical and thermochemical instability caused by increased liquid accumulation inside the crucible. For new entrants in greenfield operations, this aspect will favour the adoption of a continuous regime.

In terms of quality, for the same raw materials used in the smelting process, with continuous tapping, the time required for refining by oxidization and slagging in the refractory ladle is much greater than with discontinuous tapping. This could lead to low OPEX and higher assertiveness hit levels; increase the overall equipment effectiveness for the plant (OEE[7]).

Based on actual scenarios in industry, there are different references so far. The equipment and layout of the tapping area will also influence the changes that the operator will implement to increase tapping efficiency. The ladle car design, layout of

[7] **Overall equipment effectiveness** (OEE) is a term coined by Seiichi Nakajima[1] in the 1960s to evaluate how effectively a manufacturing operation is utilized. It is based on the Harrington Emerson way of thinking regarding labor efficiency

the post-tapping area, and the tools used for tapping are fundamentally important regarding the best regime to implement.

CONCLUSIONS

Although each tapping regime, both discontinuous and continuous, has advantages and disadvantages, it is important to evaluate the best option on a case-by-case basis. However, in general, considering the post-tapping installations that allow ladles to be exchanged with no losses and movement in the furnace area, continuous tapping looks to be a better option from the quality and environmental standpoints.

From the operational standpoint, discontinuous tapping involves lower energy losses in the tapping process and less exposure of workers to high-temperature materials and gases (although greater volumes of molten materials must to be handled in this type of regime). The operational risks are lower in continuous tapping, and process stability is easier to achieve.

The level of operational staff skill required for discontinuous tapping is higher than for continuous tapping. Therefore, new entrants building greenfield silicon plants could encounter fewer difficulties if the plant design is a flexible one, allowing operation under either continuous or discontinuous tapping. The learning curve for operators will be less steep if continuous tapping is the chosen regime for star-up. For brownfield operations, the installations and operational staff skills will affect the decision as to which regime is the best. As an example, for a brownfield expansion in a plant that is running with good results using discontinuous tapping, as long as the knowhow of the staff will be used to run the expansion, that regime will probably be the best choice for running the ’new’ furnace.

In terms operational excellence, the best regime to reach the highest efficiency levels will depend on several factors such as operational staff and planned installations (mainly the tapping and post-tapping equipment). In discontinuous tapping the risk of the reverse reaction (producing silicon monoxide) due to the high levels of liquid silicon accumulated while the tap-hole is closed could cause problems for the electrical stability in the reaction zones and electrode penetration. This could result in several issues during operation, which will adversely affect furnace output. On the other hand, the higher thermal losses during continuous tapping could adversely affect the thermal balance in the reaction zones, which will also reduce the process efficiency. To mitigate this, a hybrid approach could be used as to balance the positive and negative aspects of both regimes.

It should be stressed that there is no ’definitive best solution’ regarding a choice between the two regimes – continuous and discontinuous tapping. This should be a ’case-by-case’ decision with due consideration of the project type (greenfield/brownfield); plant installations, operational skills of staff, and engineering design.

Last but not least, some companies are nowadays operating with a kind of ’hybrid’ mode that uses either continuous or discontinuous tapping, depending on the furnace and plant conditions. This is quite reasonable and in some cases the optimum operational level could be found with this approach.

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. Mr. Domingos has more than 16 years of industrial experience in silicon and ferroalloys engineering and operations. A specialist in Metallurgy Thermodynamics and Chemical Engineer, he worked on different silicon furnaces running with all current available electrode technologies. Experience with different SAF technologies (SMS, Tenova, Elkem, Tagliaferri, Brazilian, and Chinese equipment); operational experience with continuous/discontinuous tapping in furnaces from 10 MW to 32 MW, operating with different reducing agents. Responsible for operations, process, quality, and engineering Plants in South America, Europe, and Asia.
